ALTERNATING CURRENTS:

THEIR GENERATION, DISTRIBUTION, AND UTILIZATION

BY

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PREFACE.

The original of this little book was a series of articles which found some favor in the columns of the technical press, and which the writer was requested by many readers to put into book form. The object of the articles was to discuss problems and principles in alternating currents which are difficult to understand, and to illustrate them as simply and clearly as possible. Each article was written under the assumption that the reader had a fair knowledge of direct currents and a general knowledge of alternating currents. Also they were really, more than anything else, outlines of the methods and processes on mooted questions which the writer found useful in his early studies on the subject. As human understanding is very much alike, most readers will split upon the same rocks. The articles were collected, new chapters were added, and the endeavor made to establish some continuity to the series, and the result was the first edition, which contained unfortunately some of the earmarks of separately written articles, together with some errors in context which escaped the writer's notice under the pressure of

insistent periodical publishers. Furthermore, strict accuracy was sometimes sacrificed for the sake of clearness, and it is perhaps true that in some cases analogies were carried too far, thereby introducing what might be called loose writing.

The little book was received much better than it deserved, and in response to the desire expressed by the publishers and others that it be not allowed to lapse, the writer presents this the second edition, which has been carefully gone over with reference to the removal of uncertainties. Some new matter has been added, together with some rearrangement, and the writer sincerely trusts that the result will be more continuous and accurate reading.

Such criticisms as have been ventured upon the first edition have been very acceptably expressed with a view to improvement, and entirely of a non-captious character, so that the writer desires to take this opportunity to thank his critics and to reinvite their good offices.

GEORGE T. HANCHETT.

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CHAPTER I.

Hydraulic Analogies of Inductance and Capacity Combinations.

The alternating current student, even though a moderately competent mathematician, oftentimes desires for his own understanding and information, something of a more tangible nature than proof by formulæ of the intricate behavior of current and voltage in circuits containing inductance and capacity. For this reason the writer believes that the following explanation of these phenomena with the aid of some hydraulic analogies will be interesting though elementary.

Considering an electric current to be represented by an elastic fluid flowing under pressure in a pipe, an

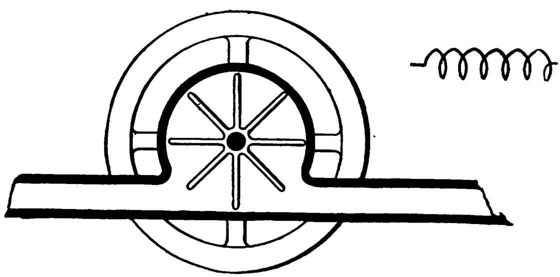


FIG. I.

inductance is well represented by a frictionless fluid motor, carrying a heavy fly wheel, as shown in Fig. 1. On suddenly starting a direct current through a line containing such a motor, the current will not be well established until the wheel is well

under way, after which it will proceed hindered only by the friction or resistance of the apparatus.

Similarly in starting a direct current through an inductive coil it grows in value quite slowly, being hindered by the counter E. M. F. or electro magnetic inertia of the coil, which gradually disappears as the current becomes steady, and finally the current flows limited in volume only by the ohmic resistance of the circuit.

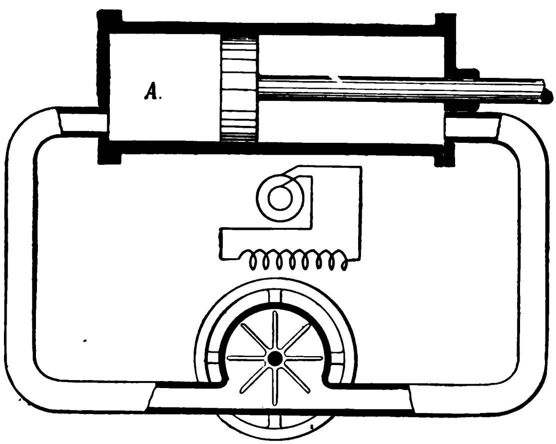


FIG. 2.

If this wheel and pipe line be subjected to an alternating flux of fluid pressure as shown in Fig. 2, the current flux being produced by operating a piston in a cylinder, A, back and forth, it is evident that due to inertia of the fluid motor and its fly wheel, the latter will not follow the movements of the piston promptly. The movements of the piston dictate the pressure, while the velocity of the wheel is proportional to the flow of current. It needs no

mathematician to see that the maximum velocity of the wheel will not correspond to the maximum pressure on the piston, but will lag behind it; in other words, the current will lag behind the pressure. The wheel is continually opposing the piston impulse by its stored energy, and the net result on the current is to reduce it and make it lag behind the impressed impulse.

Similarly a coil of wire on which an alternating E. M. F. is impressed will continually oppose its

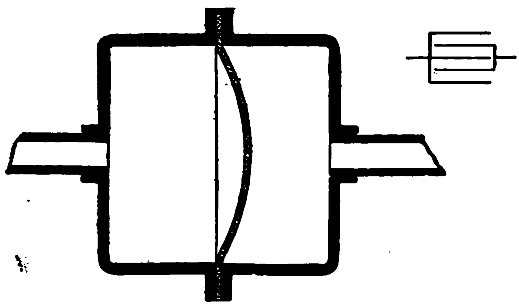


FIG. 3.

stored energy to the original impulses, the net result being a current of lesser value, the maximum surges of which do not correspond with the original impulses, but lag behind them.

Returning to the pressure analogy, it is plain that the current in the pipe is urged forward and back due to the joint efforts of the primary pressure and the stored energy of the fly wheel. To appreciate what follows it must be remembered that the fluid must be an elastic and not a non-compressible medium. It will be seen at once that the current is urged back and forth by the joint

efforts of the primary pressure and the action of the paddles of the wheel. The latter force cannot be neglected. Its ill-timed pulses reduce the current and displace it in phase. The energy of the system is therefore divided into two parts, one of which serves to overcome the friction of the

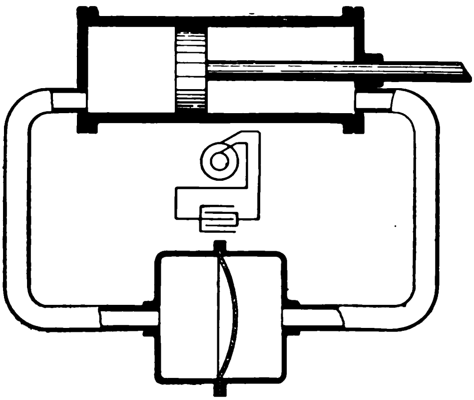


FIG. 4.

fluid and is lost in this way, and the second is employed in overcoming the inertia of the fly wheel, which, however, returns the power it so received to the system.

The reverse motion of the paddles against the primary impulse serves to store up fluid pressure, which presently reacts and assists in starting the wheel the other way. This energy is a sort of rebate on the energy delivered by the piston and may be called an idle component, while the energy absorbed in overcoming the resistance is called the working component.

The electric analogy of this is the coil of wire on

which is impressed an alternating E. M. F. One portion of the apparent energy is absorbed by the resistance of the circuit and is true watts. The other is momentarily absorbed as magnetic energy in the coil and redelivered to the generator between impulses and is the wattless component.

Electric watts are the product of volts and amperes, and it is sometimes customary to carry this wattless feature into its component products. There are two ways of looking at this problem, both of which are merely convenient and highly artificial.

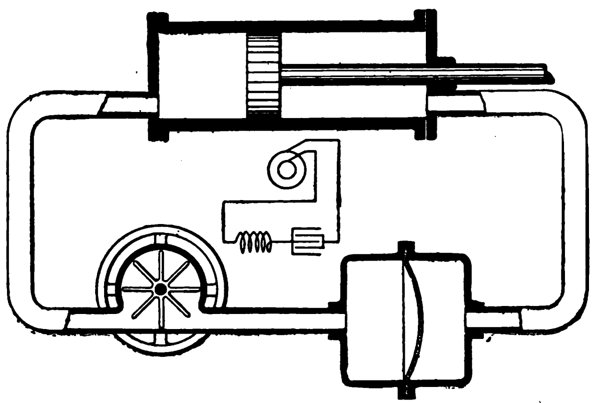


FIG. 5.

One is to assume that the voltage is a pressure divided into two parts, one of which is effective in forcing the current through the ohmic resistance, and which multiplied by the current gives the true power. The other pressure component is utilized in balancing off the elastic reactance of the coil, and multiplied by the current gives the false or fictive

some oscillating of the flow on either side of the condenser before the current comes to rest, thereby carrying the analogy still further.

An electric condenser acts in the same way when connected to a direct current pressure. A charge flows into the condenser till its terminals rise to a pressure equal to that applied. Disconnected from the line it retains its charge, and if its terminals be connected together a discharge takes place which is of an oscillating character and which finally brings both sides of the condenser to the same pressure.

If an alternating pressure be applied to the condenser as in Fig. 4, it is plain that the current will flow very rapidly into the condenser until the diaphragm begins to be tightly distended and its counter pressure begins to oppose such flow. Therefore the current will have a maximum flow in the early stages of charging even though the pressure be light, the minimum flow in the later stages of charging even though the pressure be heavy, for it is counter balanced by a correspondingly heavy pressure in the diaphragm. The maximum current therefore precedes the maximum pressure, or in other words the current leads the electro motive force. In precisely the same way does an electric condenser receive and discharge current into alternating current mains and lead the current impulses ahead of those of E. M. F. by its action.

Current displaced in phase with reference to impressed electro motive force always results in wattless power, and in this case it is even easier to see how the distended diaphragm urges fluid against the retreating piston, making the latter easier to move and thus returning energy to the prime mover.

Wattless electric energy is returned to the power house generator somewhat differently but none the less truly. The current of displaced phase enters the generator winding and its maximum value occurs when the winding is under the proper pole to drive the machine as a motor, thus making it easier to turn. The more the phase is displaced the more pronounced will be this effect and the easier the generator will be to revolve. Thus a machine may have full pressure and current but by reason of the displaced phase of the current may be really generating and delivering a mere fraction of its apparent power.

In Fig. 5 is shown a hydraulic inductance and condenser connected in series and subjected to an alternating fluid pressure. After the oscillating of the rubber diaphragm and the alternate rotations of the wheel are well established, it is plain that as the current dies away to zero preparatory to an impulse in the other direction the motor wheel will continue its rotation in the same direction and endeavor to maintain or keep up the dying current similarly to the Lenz law of electro-magnetic induction. The condenser on the other hand will upon the dying away of the line pressure tend to force a current back by means of its rubber diaphragm, thereby opposing the current which the inductance is trying to maintain. Thus it is plain that with a properly proportioned inertia, and diaphragm capacity, the one could be made to neutralize the other, and currents could be established in the combination in phase with the piston impulses and depending only on the friction of the pipe line and the pressure. The motor wheel would keep step with

the piston because it would have the reaction of the rubber diaphragm to help it check its motion and start it in the other direction.

It is plain that the pressure around either condenser or motor may even exceed the line pressure owing to the combined action of the rubber diaphragm and the pressure created by inertia of revolving motor, all of which tends to raise the pressure in the line connecting the two.

In the same way a genuine inductance and capacity may neutralize each other, so the current would flow through the circuit in accordance to Ohm's law, and the pressure around either of the two devices may far exceed the line pressure, although their sum added vectorially, that is to say, with due reference to phase relation, will be exactly equal thereto.

In Fig. 6 is shown a hydraulic inductance and condenser connected in parallel and subjected to an alternating pressure. This action of these two devices under such conditions is just as simple as in the preceding cases. The alternating current pressure stores up fluid in the condenser and provides a velocity of the fluid motor in the proper direction. As the line pressure dies away to zero, the condenser instead of reacting into line, discharges into the fluid motor which is already revolving in the right direction to receive such a discharge, and the fluid motor instead of by its inertia tending to draw current from the line, draws current from the condenser. Properly proportioned the one could be made to supply the false power needed by the other, and the current may thus be made to flow through the system in pro-

portion to the resistance of the circuits and the pressure.

It is plain that the current in the local circuit between condenser and fluid motor may be greater than the line current because of the combined action of the pressure of the condenser and back draft of the motor. The exact analogue exists in the equivalent electrical combinations in which the current plays between the inductance and capacity in the same way. The device is used with induction motors having a large power factor, and the condenser is said to supply the wattless current while the line supplies the working current. If the power factor of the motor is less than .5, the current in the condenser circuit will exceed the line current, for the power factor of any reactive device is the ratio between the true and apparent watts that the device receives. These simple analogies will be of great assistance to the novice and even to those more skillful in figuring out the reactions of alternating current phenomena.

CHAPTER II.

ALTERNATING CURRENT PRINCIPLES.

The alternating current has been described by analogies given in the preceding chapter. The complete conception of its identification is very difficult without such assistance. The beginner in alternating currents will remember the well known direct current law

$$C = \frac{E}{R}$$

and its various modifications

$$E = C\ R$$

$$R = \frac{E}{C}$$

together with the power equations

$$W = C^2\ R$$

$$W = \frac{E^2}{R}$$

These are absolutely true in the case of alternating currents *always provided that when the formulæ are used the real E is selected.* Unlike direct currents, the electro motive force at the terminals of the circuit is not always the electro motive force which is effective in forcing current through the same and which should be used in the foregoing equations. Current flowing through the circuit is very naturally proportional to the sum of all the electro motive forces the circuit contains, just as is true in direct currents. For instance, if we have a direct current

dynamo generating 100 volts and supplying current to a motor, the resistance of which was ½ an ohm, we could not reasonably expect a current of 200 amperes to flow. It would be necessary to allow for the back electro motive force of the motor, which should be subtracted from the impressed electro motive force of the terminals.

Similarly in an alternating current circuit, if it is found that the application of the alternating current voltage to the terminals of the circuit creates other electro motive forces these must be taken into account and properly substracted from or added to the impressed electro motive force before we can find the electro motive force that is really effective in forcing current through the circuit.

In the simple case of a coil of wire wound upon an iron core, the application of an alternating current electro motive force causes a current to flow in the coils. This generates in the coil a magnetic field which fluctuates up and down, reversing with the current. A fluctuating magnetic field generated within a coil generates an electro motive force with the same, and even if the coil itself carries the current which produced the field, it is no exception to the rule. This electro motive force of self induction, as it is called, seriously interferes with the impressed electro motive force and prevents the former from sending through the coil a very large current. The current that is sent through the coil is proportional to an electro motive force which is a combination of the two, and is called the resultant thereof.

To determine just how this resultant is formed by its two components demands a more careful analysis

of the performance. This will be treated geometrically for greater simplicity.

In geometrical diagrams it is very common and convenient to represent the magnitude of a quantity by the length of a line. Almost every one has seen diagrams illustrating the relative population of large cities. For instance the population of New York would be represented by a line of certain length: of Chicago by a line of certain lesser length, of St. Louis a lesser length still, and so on, and it is plain that if we can represent a number of people by a line, we can represent amperes, volts or watts, or any other quantity in the same way. To this end we will construct a diagram as shown in Fig. 1. In this diagram vertical lines or distance represent volts, and horizontal lines or distance represent units of time. The diagram is so drawn that one inch horizontal represents 200th part of a second, and 1 inch vertical represents 200 volts. As an alternating voltage begins at zero and slowly rises to a maximum and then reverses and repeats the operation, it can, therefore, be represented by a curved line shown in Fig. 1, and it is easy to see that if we wish to know the amount of the alternating voltage at any particular instant of time, we have only to select this time on the time axis and measure the vertical distance below or above the line. It seems hardly necessary to say that the wire or dynamo does not contain any such sinuous line of flow as shown in the diagram, but the statement is justified by the fact that it has been the experience of the writer that many who have seen such diagrams as this have thought this to be the fact. Fig. 1 is simply a con-

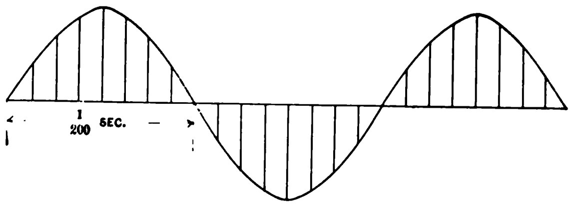


FIG. 1.

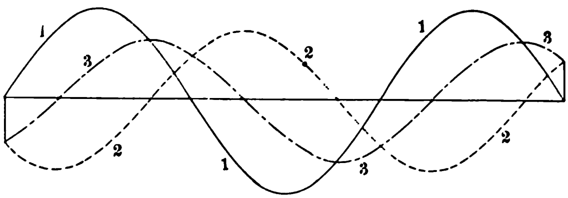


FIG. 2

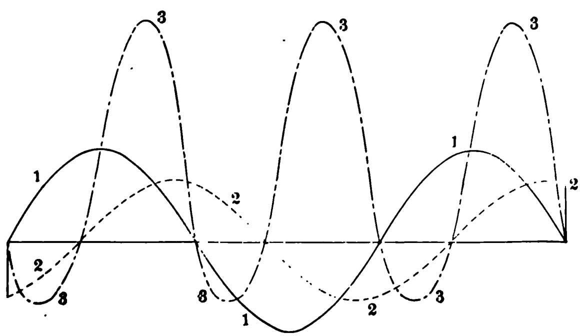


FIG. 3

venient way of showing the various values an alternating current voltage obtains throughout the cycle.

Now let us suppose that curve 1 in Fig. 2 represents the various values that the impressed voltage obtains throughout the cycle, and that curve No. 2, represents the various values which the self-induced voltage obtains. Curve No. 2, it will be noted, is not in step with curve No. 1. Its highest value comes at a distinctly later time than that of curve No. 1, and it has been purposely so chosen because the self-induced electro motive force is never in step with the impressed electro motive force for the following reason:

The self-induced electro motive force is obviously at its highest point when the number of lines of force induced by the coil are changing most rapidly. This happens when the current is rapidly increasing or diminishing, and not when it is maintaining a momentary steady value at its highest point. Consequently the high value of the self-induced electro motive force does not correspond with the high value of the current, but lags behind it, and it remains for us to determine what its relation will be to the impressed electro motive force and to the resultant electro motive force.

The first thing to do is obviously to combine these two curves of electro motive force into a third or resultant curve, for the current will flow in exact proportion and step with that resultant. At any one instant a point on the third curve will be the sum of the vertical distance of the two other curves. This will be the simple arithmetical sum of the two vertical distances or ordinates when the curves are both

below or both above the zero line, but when one is above and the other below, it will be their difference. Curve No. 3 shows the resultant curve constructed in this way. It will be found to be a curve very similar to the other curves having just as many crests to the second but of a smaller maximum value, also lagging behind the impressed curve, but leading, that is to say, occurring earlier than the self-induced curve. The current is proportional to this resultant curve, therefore the current impressed upon the line lags behind the electro motive force and is very much smaller in value than it would be if the electro motive force were not interfered with and were the only electro motive force in the circuit.

Fortunately an important relation obtains between the current that is flowing and the curve of induced electro motive force. The lines of force to which the induced electro motive force is due are in step with the current, and it is well known that an electro motive force due to lines of force in motion is greatest where the time rate of change is the greatest. It is obvious that the current and with it the lines of force are changed most rapidly when the current is passing through zero, and that when it is a maximum the flow of the current and of the lines of force is for an instant steady. Therefore the curve of induced electro motive force will be a sine wave with its zero point corresponding in time period to maximum current, and its maximum point corresponding in time period to zero current. In other words, it will be displaced therefrom exactly a quarter of a ·cle.

Having demonstrated these facts, we are now prepared to determine the true power of the lagging current. It is possible for us to determine the impressed electro motive force very readily. We can also determine the actual current flowing. We have no obvious means of determining the resultant electro motive force, which is the real electro motive force by which we must multiply in order to get the power. If we multiply by the impressed electro motive force we will get a result that is too large. For this purpose it will be well to consult diagram in Fig. 3. In this case curve No. 1 represents alternating current and curve No. 2 represents the alternating voltage, and as will be seen the voltage lags behind, that is to say, it occurs later. If we combine the impressed voltage with the current, multiplying them together, ordinate by ordinate, we shall get a curve such as No. 3 in Fig. 3. This will be the true curve of power, for it obviously represents the power at every instant, for it takes the voltage at the time multiplied by the current at the time, and consequently takes account of the fact that their maxima are shifted with reference to one another. This power curve appears both above and below the zero line, the upper half represents positive power and the lower half represents negative power. The meaning of negative power is a little confusing and many students are inclined to think that negative power is power flowing in one direction and positive power, power flowing in another. Power itself can have no direction. A stick of dynamite may contain a great deal of power and it may be carried from place to

place, but while it is being so carried, the power itself is not acting in any given direction. A quantity of heat, which is also power, has no direction of itself. Therefore positive power and negative power cannot mean direction. If we were to apply the terms positive and negative to heat, we should consider negative power as the absence of heat and if we combine a large quantity of positive heat with a smaller quantity of negative heat, we should expect a lesser quantity of positive heat. So it is with this alternating current energy. The real power which is obtained is the difference between the areas of the upper and lower crests. The upper crest is the power sent out by the dynamo, and the lower crest is the power returned to the machine by reason of the inductive reaction of the coil which is in circuit.

If the current and voltage curves are arranged as shown in Fig. 4, in which the maximum value of the voltage occurs at the same time that the minimum value of the current obtains, the result will be as shown below, in which case the positive and negative powers are practically equal and the actual power exerted in the circuit is zero. In such a case the current is sometimes said to be wattless and sometimes the volts are considered to be wattless. As a matter of fact, this is only a convenient way of expressing the matter, but it is sometimes very confusing. It is perfectly proper to apply the expression wattless to a portion of either volts or amperes when multiplying the two together to determine the power, that is as far as the accuracy of the result is concerned, but there is no physical reason why this should be done.

If the current is in phase with the electro motive

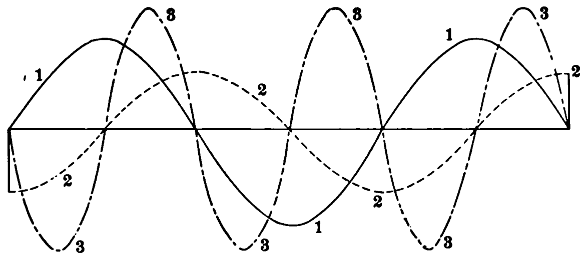


FIG. 4

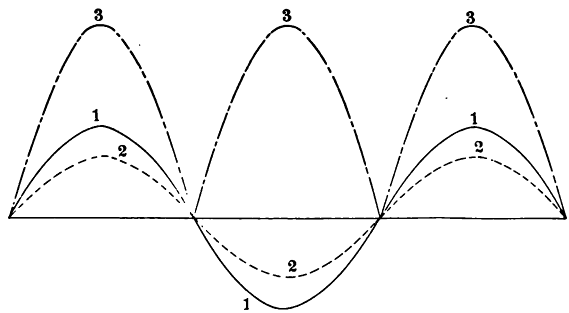


FIG. 5

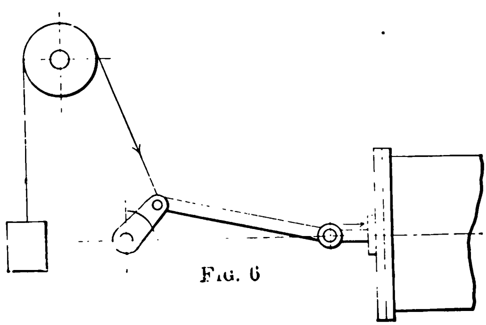


FIG. 6

force as shown in diagram No. 5, the power curve will appear above the zero line, and the true power will also be the apparent power, as there is nothing to subtract therefrom.

This matter of wattless power is one of great importance, as all alternating current circuits have a certain percentage of it, that is to say, a certain percentage of the power is reacted back into the dynamo. Circuits coiled upon iron, condensers, structures involving these constructions have a very large percentage of power returned to the dynamo, while incandescent lamp circuits have but very little wattless power. The ratio of the apparent power to the true power is called the power factor and it must always be applied in the power equation. Thus a motor which is absorbing 20 amperes at 100 volts, that has a power factor of .90, is not absorbing 2 kilowatts, but 20 x 100 x .90 or 1.8 k. w., for allowance has to be made for the power factor. The generating dynamo, however, has to be as strong and rugged as if it carried the whole current and whole voltage in phase and in step, for there is no guarantee as to what the nature of the load carried will be. It may be all lamps or it may be all coils and motors, in the one case involving practically unity power factor and in the other perhaps a power factor having a very considerable effect upon the result. Consequently it must be able to stand the full rated conditions. It is easily possible, however, for the generator to be carrying full current, but for it to be so shifted in phase with reference to the generating voltage that there is almost no energy being transmitted to the line, but most of it is being reacted from the line and helping to

drive the dynamo as a motor, as has been shown in the foregoing chapter. Consequently the generator has a very easy duty, but it will be seen that the generator wires are current loaded to the limit and if any more current were placed upon them, the armature conductors would begin to overheat. In fact, the situation is precisely analogous to that of an engine arranged as shown in Fig. 6. To the crank of this engine is attached a cable, and as the crank descends, the cable hauls up a heavy weight. As the crank ascends, however, the weight helps the engine to turn around. No useful work is done, for whatever work is expended on the weight is presently returned to the system, but it is evident that the engine must be built sufficiently strong and rugged to stand the mechanical strains which this weight will put upon it, even though it may be doing at its shaft only one or two useful horsepower. The dynamo with the wattless load is precisely in the same predicament. Its useful power is a small percentage of the apparent power. Hence wattless current or wattless power is a very undesirable phenomenon for the central station man, and must be taken into consideration in all his calculations. For instance, in installing induction motors, he must make his transformer larger in horsepower than what is really required, in order to make the wires sufficiently large to allow this useless exchange of power between the motor and transformer. It is commonly figured that the kilowatt capacity of the transformer should equal the horsepower capacity of the motor.

In the case of a condenser on a simple alternating electric circuit, the current will obviously flow into the condenser most rapidly when the condenser is

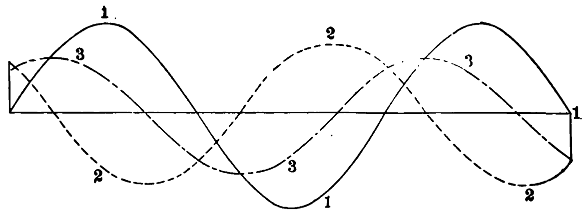


Fig. 7

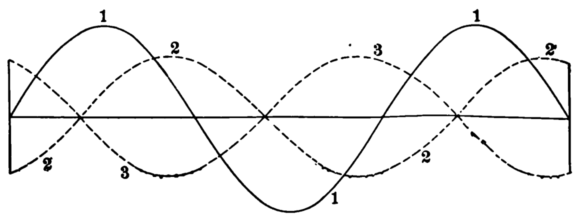


Fig. 8

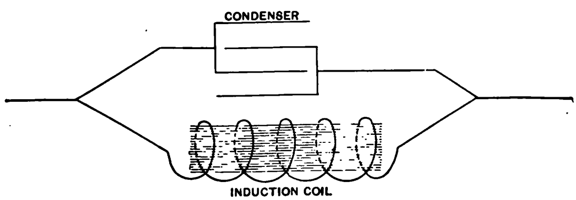


Fig. 9

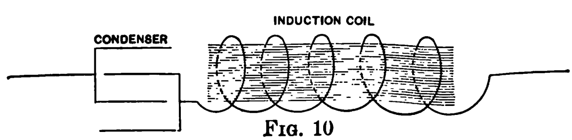


Fig. 10

uncharged, and the flow into the condenser will be slow when the condenser is fully charged; in other words, the impressed electro motive force on the condenser lags behinds the current, that is to say, the current attains its maximum value first. Consequently on the diagram, these electro motive forces are combined as shown in Fig. 7; the back E.M.F. of the condenser leading the impressed electro motive force, and the resultant of the two also leading the impressed electro motive force an intermediate amount, and the current which is proportional to this resultant leads also. Being displaced in phase, however, the current and voltage curves combine and involve a power factor as before.

In an alternating current circuit, however complicated, there can be only one current flowing at any one time in any one part of the circuit. This current is the resultant current of any branch currents which may be flowing into this particular part of the circuit. Thus we may have a diagram such as is shown in Fig. 8, in which two currents, one leading the electro motive force and the other lagging behind. Equal amounts of opposite sign may be added together and produce practically a zero result, that is to say, one will compensate for the other. Thus in Fig. 9 we may have in parallel on an alternating current circuit a coil wound on iron and a condenser. Either alone might call for a substantial current from the mains which would be wattless in its character, the one leading the electro motive force and the other lagging, but the currents of the two if combined, and simultaneously applied to the circuit, will produce in the supply line a very small current indeed, although the circulation of cur-

rent between condenser and coil may be quite large, as pointed out in hydraulic analogy in the previous chapter.

With the condenser and coil in series, as shown in Fig. 10, there is only one current in the circuit, but we know that in the coil there is a lag between the current and electro motive force, and in the condenser there is a lead; consequently, as the current is the same in all parts of the circuit, the electro motive forces about the condenser and coil respectively must be widely out of step with each other and so indeed it will be found. They will often be very much larger than the impressed electro motive force on the circuit, but when added together by the method of curves, will produce as an impressed electro motive force which creates them very much smaller than either component.

The foregoing method of combining electro motive force and voltages for alternating work will, perhaps, enable the student to have a more concrete view of what actually occurs in the circuit but it is by no means a convenient method of attaining the result. Therefore, for complete mastery of the subject, the student must pay particular attention to the simpler methods of adding and subtracting alternating current electro motive forces and voltages with due regard to phase. Of these methods there are two, the geometrical method, which is sometimes called the graphical vector method, and the algebraic method, which involves the use of complex quantities, and which was first introduced by Charles P. Steinmetz. Both should be carefully studied, but the vector method being the simplest, deserves the more immediate attention of the beginner.

CHAPTER III.

SINGLE PHASE CONSTANT POTENTIAL TRANSFORMERS.

THE LAW OF TURNS AND VOLTAGES.

A complete knowledge of transformers in all their possible forms and performance is essential to those who install and operate them. A transformer of whatever type consists of an iron core, usually of such form as to completely encircle the turns of one or more copper coils which may be wound upon it. If a copper coil wound upon such a core is excited with an alternating current, an alternating flux of magnetism will be produced in the core. The effect of this flux is to induce an electro motive force in every turn of copper wire wound around the same, whether it be an independent coil or the identical coil in which the current is impressed from the outside source. This electro motive force is the result of a combination of several electro motive forces according to conditions and is practically equal to the impressed or primary electro motive force divided by the number of turns on the primary coil. It is in almost direct opposition to the impressed electro motive force in phase, that is to say, when the outside supplied source of electro motive force has a maximum positive value, the force which is generated in each coil by means of the magnetic flux, has a very nearly equal and opposite negative value. So nearly in fact are these electro motive

forces equal in magnitude and opposite in relation that the impressed electro motive force on the primary coil is almost balanced by the induced electro motive force within it, so that the current flowing in response to the slight difference between these two forces is very small indeed. It is this current which does the magnetizing, and this is therefore sometimes called the magnetizing or leakage current.

It is evident from the foregoing that if there be few primary turns with a high voltage upon them, there must be much flux in order that the necessary high back electro motive force just referred to shall be produced. If the iron circuit is not adequate in such cases, its intense magnetism will cause it to hum loudly and the iron will become very hot. Moreover the magnetizing current will be large and the impressed electro motive force will differ more largely from the back electro motive force both in magnitude and in its opposite character of phase relation. These considerations fix the proper number of turns and amount of iron used in transformers. If for instance we were to place a transformer designed for 50 volts upon a 100 volt circuit, we should not by so doing increase the turns. The back electro motive force must, however, nearly equal the impressed electro motive force and therefore the flux must be practically double. The iron would sing and become hot, the regulation would be poor, in short, the combination would not be suitable.

In order that we may understand the law of voltages more clearly, let us consider a concrete case. Let us suppose that we have a suitably designed iron

core and have wound upon it a coil of 6 turns, as shown in Fig. 1. To this coil we apply an electro motive force of 6 volts. A back electro motive force of almost 6 volts is immediately generated within the coil and very little current can flow. Each turn is therefore capable of producing practically one volt. If we wind on the same core an independent secondary coil of two turns we should have generated in each turn an electro motive force of one volt because it surrounds the same flux of magnetism. If the coil had two turns, the voltage would be 2, and so on. Therefore it is plain that by selecting the proper number of turns we can have the secondary voltage anything we please.

If we attempt to draw current from the coil of two turns which we have previously wound as a secondary upon the core, and draw from the same one ampere, it must be noted that this ampere flowing in response to the electro motive force in opposite phase to the primary force, generates a demagnetizing effect of two ampere turns. The effect on the primary coil is to cause the same to absorb from the line enough current to counterbalance this demagnetizing action. As there are 6 turns in the primary coil, only one-third of an ampere will be required in order to produce 2 ampere turns. Therefore in drawing 1 ampere at 2 volts from the secondary, we absorb in the primary one-third of an ampere at 6 volts, the same amount of energy. Furthermore and most important this ampere turn in the primary will exactly balance the ampere turn in the secondary whether the secondary current lag or lead its electro motive force. Thus the introduction of

a transformer into a circuit reflects back on the generator all the lagging or leading effects due to inductance or capacity in the secondary receiving circuit.

These statements are somewhat modified because in this process a certain amount of energy is lost in heating the copper coils and in magnetizing the iron, but they are nearly enough the fact to answer all practical purposes. A simple

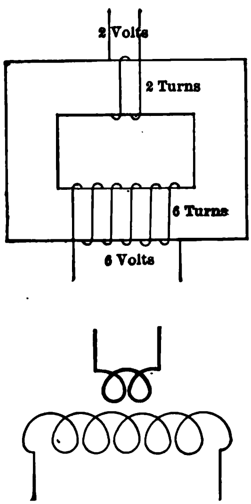


FIG. I.

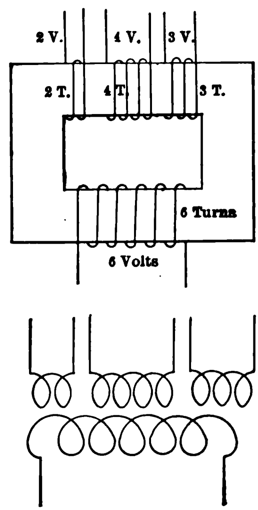


FIG. 2.

transformer of the form thus discussed is illustrated in principle in Fig. 1. Its diagrammatic representation, such as is used in transformer connection diagrams, given in the lower portion of the figure.

It is plain, therefore, that we could wind a transformer with a number of secondary coils of different voltages and current capacities, all receiving their

energy from the flux of magnetism generated by the primary coil. Composite transformers of this class are not uncommon. For instance a transformer may be wound with a single primary receiving current at 10,000 volts. It may have several secondaries, one adapted to deliver 110 volts for lighting purposes, and the other 340 volts to supply to a rotary converter for railway work, and if desired still another to supply current at 500 volts to operate an induction motor. In fact the combinations that can be obtained in this way are practically infinite. A composite transformer is shown in diagram in Fig. 2.

The primary coil of the transformer may be also sub-divided into two or more parts. Remembering

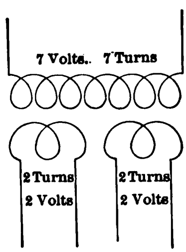


FIG. 3.

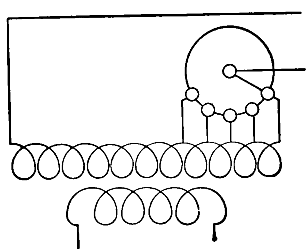


FIG. 4.

that the flux and the performance of the transformer depend on the primary voltage divided by the number of turns, it is plain that if in the concrete case which we assumed a moment ago we excite a coil of 50 turns at 50 volts, we should have the same effect magnetically as if we excited 100 turns at 100 volts. It is very common to divide the primary coil of a transformer into at least two parts so that they can

be operated on either of two voltages, one of which is one-half the other. Such a transformer is shown in principle in Fig. 3.

Sometimes it is convenient to have the secondary voltage adjustable. To effect this, one terminal of the secondary is connected to the circuit to be supplied, and the other to the arm of a multiple contact switch which will cut in more or less turns and vary the volts correspondingly. This arrangement is used with large central station transformers where it is desired to raise the voltage on the line as the load comes on and thereby compensating for the volts lost in the transmission so that the volts at the receiving end of the line may be constant. A trans-

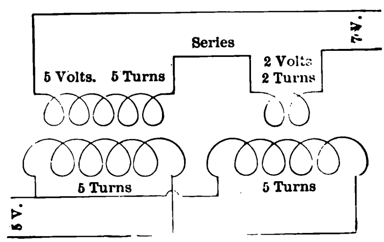


FIG. 5.

former with an adjustable secondary is shown in diagram in Fig. 4.

A transformer, as its name implies, transforms energy. It cannot create it. For every watt that is drawn out of the secondary or secondaries in a transformer a corresponding watt must be absorbed by the primary from the line, plus a small additional amount to make up for the losses of the device, so small that for the purpose of this discussion it may

be neglected. As the previous paragraphs have shown, for every ampere turn that the secondary current imposed on the core a counterbalancing ampere turn must appear in proper phase relation in

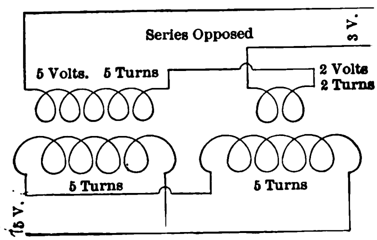


FIG. 6.

the primary coil so as not to disturb the magnetizing flux which is doing the work.

In two coils producing equal ampere turns, one of which has more turns than the other, say ten times as many, it is evident that the coil of many turns needs only one-tenth the current that the coil of few turns requires in order to produce a balance. It is also plain that the copper wire of the coil of many turns need only be one-tenth as big as the copper wire of the coil of few turns because of the lesser current that it has to carry. As there are ten times as many turns however in the coil of many turns, the volume of copper of both coils is the same, therefore the copper in the primary of a well designed transformer is practically equal in volume to the copper in all of the secondaries put together. In the simple case of our 6 volt transformer, if we have a coil of 6 turns of No. 10 for the primary, the secondary

producing two volts must have a coil of wire of two turns only but equal in area to 3 No. 10 wires because it has to carry three times as much current as the primary coil, if it is to deliver the full amount of

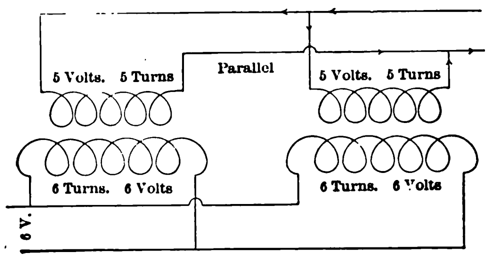


FIG. 7.

energy which the primary coil is capable of absorbing. If we are content to take from this coil a lesser amount than the primary is capable of transforming, we can make its secondary wire area correspondingly less. This is sometimes the case in composite transformers where we wish to transform a part of the primary energy for one purpose and another part for another.

The electro motive forces of one or more transformers, all excited from the same primary source, can always be connected in series, and if their values are alike they can be connected in parallel. Although an alternating current transformer is popularly supposed to have neither positive or negative terminal, yet due regard must be had for the proper selection of terminals in multiple and series connections. Taking the diagram shown in Fig. 5, where

we have two transformers excited from the same primary mains, if we connect them as shown in the figure, we shall have the secondary electro motive forces added together, which may answer our pur-

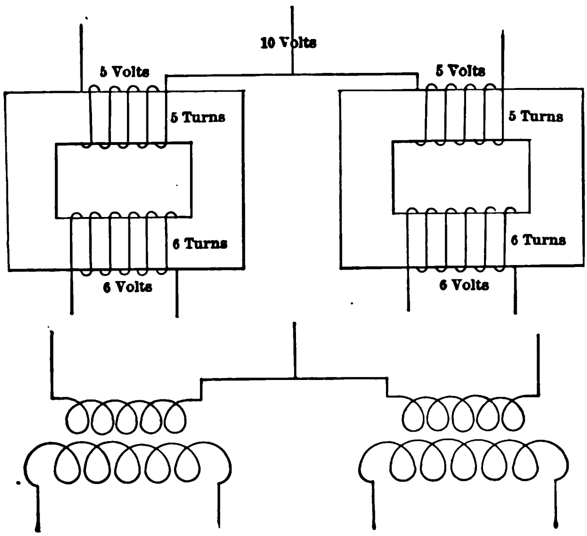


FIG. 8.

poses in some cases. If, however, a mistake was made and the transformers were connected as shown in Fig. 6 the electro motive forces would be subtracted from each other and only the net result would appear at the terminals. If the two transformers were equal in voltage, there would be no difference of potential at the terminals in the case of this second connection.

The voltmeter is of lesser assistance in this case, for even though it be an alternating current voltmeter it does not distinguish between like and unlike terminals. In the case of lighting circuits, where this problem frequently arises, the best way to determine whether the transformers are correctly connected is to make one connection and try the free terminals with a lamp equal in voltage to the voltage of the two transformers added together. If this lamp lights, they are connected in series and unlike terminals are connected together. If not, like terminals are connected together. This device is very useful in identifying when it is desired to connect in parallel, as shown in Fig. 7.

Series connection of transformer secondaries, as shown in Fig. 8, is much used to supply three wire systems. These may be supplied from two transformers, as shown in the figure, or as in Fig. 9, from a single transformer with two secondaries wound upon the same core.

Parallel connection is sometimes required when it so happens that a very heavy circuit of lamps or motors is to be supplied, and the transformers at hand are not suitable for the work but several must be used. It is important in connecting transformers for parallel work to try the lamp test before making the second connection, for if by some mistake they should happen to be connected in series, the making a second connection, as in Fig. 10, will cause a short circuit which will call for such a heavy current from the secondary that the primary will absorb a correspondingly heavy current to counteract the demagnetism and supply the energy, and in so

doing will blow out the fuse. With a lamp in circuit as a preliminary test, if such a combination occurs,

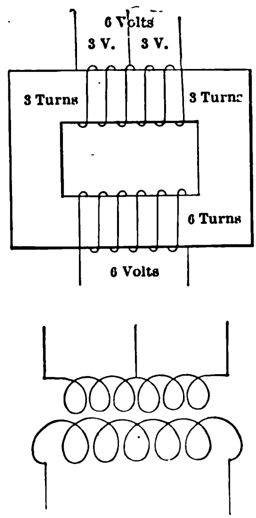


FIG. 9.

the current that will be drawn will be very small and

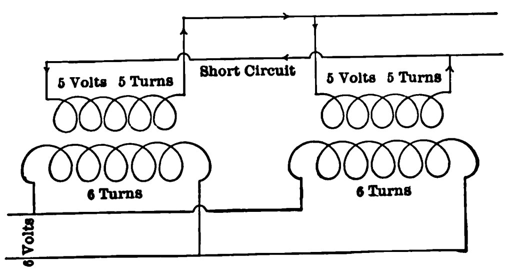


FIG. 10.

its presence will be betrayed by the lighting of the lamp. The ends of one of the transformer secon-

daries should then be reversed, and if the lamp fails to light on the second trial, the two ends to which it was connected are alike and may be safely coupled

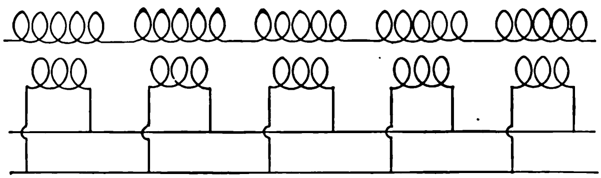


FIG. 11.

together and the two transformers are ready for parallel operation. It must be further appreciated that the transformer voltages must be exactly alike for safe parallel working, for otherwise they will exchange currents. In short they will behave ex-

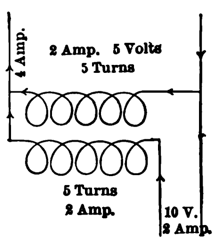


FIG. 12.

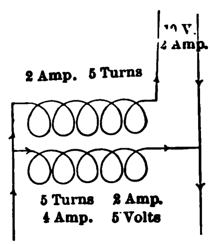


FIG. 13.

actly like dynamos of unlike voltages in parallel. For this reason it is best to confine parallel working to transformers of the same make, type and capacity for slight differences are serious and are likely to obtain.

A precaution should be observed in connecting transformers in series for the purpose of generating very high electro motive forces. Taking Fig. 11 as a concrete case, we have here a number of transformers whose primaries operate at 100 volts, and are all in parallel, each being connected across the same source of supply. The secondaries, each of 1,000 volts, are connected all in series to produce 5,000 volts. It must not be forgotten that the full potential is impressed between primary and secondary on the insulation of the two transformers at the end of the series, and unless they are built for such work they will break down.

An interesting modification of transformer arrangement is known as the auto transformer. In this arrangement the primary and secondary coils are connected together. Figs. 12 and 13 show two methods of connecting the auto transformer. In the first method the case is made concrete so as to be clearly illustrative. In the one case the primary current passes through one section of the coil and thence through the load or receiver circuit back to the mains. In so doing it loses 5 volts leaving only 5 on the receiver circuit, but by reason of the flux produced by the core, 5 volts is generated in the other coil, which being in parallel with the receiver current delivers current thereto, in fact just the same amount as the primary circuit. In this way the receiver circuit receives double the current at one-half the voltage, but as the secondary of this transformer supplies only one-half of the receiver current, only one-half of the energy is transformed. In this way a 1 kilowatt transformer might serve

to transform 2 kilowatts because one of the kilowatts would be received directly from the primary circuit, and the other by means of transformation through the secondary circuit. This would be cheaper than to build a transformer which would transform the whole two kilowatts and the losses would be less. It is therefore much used.

The converse arrangement is explained a little differently. In this case one of the divisions of the coil is connected to the line and receives current therefrom, the load is connected across the terminals of the two coils which are in series. The primary current in passing through its coil generates a flux which induces an electro motive force in the other half of the coil, and therefore such current as flows through the secondary circuit is urged both by the primary electro motive force and by the electro motive force of the other section of the coil connected in series therewith. The current in the coil connected directly to the primary mains is equal and opposite in direction to the current flowing in the secondary circuit, necessarily so to compensate for the demagnetizing action of the coil not connected across the primary mains, and incidentally conforms to the law of the conservation of energy. That is to say, the receiver circuit receives one-half the primary current at double the primary voltage.

For cases where the primary and secondary voltages are closely alike, the auto transformer is by far the best arrangement. For instance, where it was desired to transform from 100 volts to 110 volts, a suitable auto transformer would be one-eleventh the capacity of a transformer on the ordinary plan.

CHAPTER IV.

SINGLE-PHASE TRANSFORMERS—CONTINUED.

The transformers discussed in the preceding chapters have all been supposed to receive their energy from a source of constant potential. It is often desirable to use transformers in other ways in which the potential at the primary is not a constant quan-

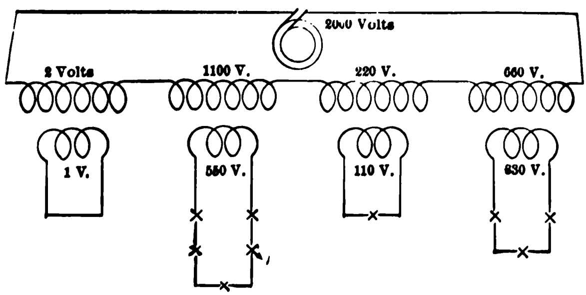


FIG. 1.

tity. In any case the transformers will behave in strict accordance with the laws laid down in the preceding chapter, that is to say secondary voltage will bear to the primary voltage the same ratio as the primary and secondary turns. It is understood that the primary coil is the coil that receives the energy, and the secondary coil the coil that delivers it.

Prominent among the cases where constant potential is not employed is that of the constant current series transformer. In principle it differs not at all from the transformers for constant potential ser-

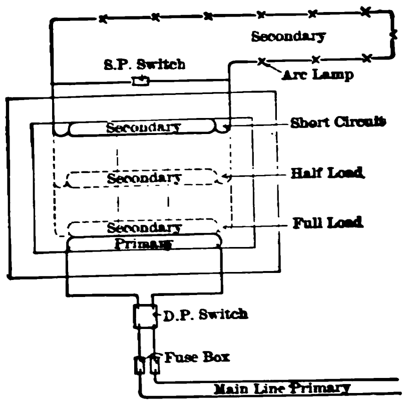


FIG. 2.

vice excepting that its coils and core are differently proportioned for the currents and flux they are to

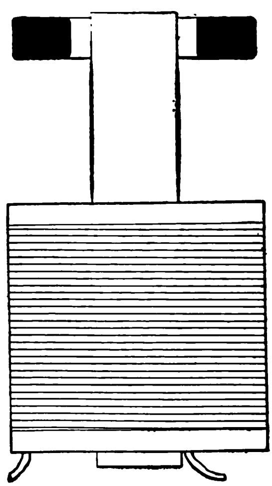


FIG. 3.

carry. Such a system of transformers is usually used in series, and the current in the primary circuit is kept constant by proper regulating means identified with the source of supply.

Let us see what the effect of such a transformer will be with various resistances in its secondary or

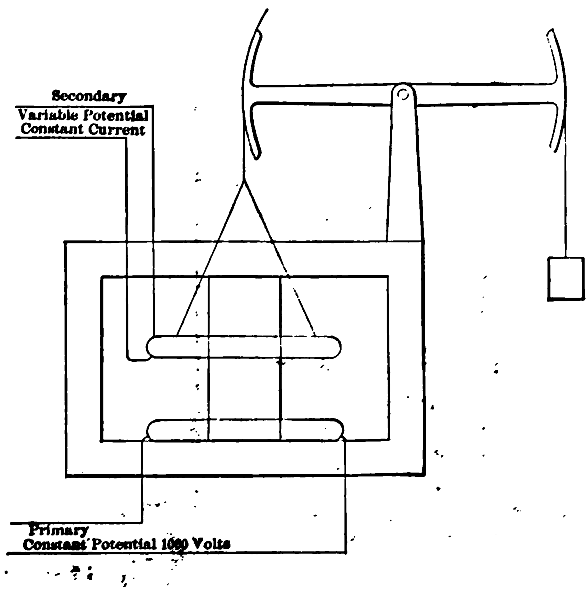


FIG. 4.

receiver circuit. In the first place consider the secondary coil to be short circuited. The current in the primary coil will not rise to a large value as in previous cases because it is kept constant. The current in the secondary coil will therefore rise to a value sufficient to almost neutralize the magnetizing

action of the primary, leaving a small margin in its favor to produce a magnetizing flux through which the work of transformation is performed.

FIG. 5.

Let us now suppose that considerable resistance is inserted in the secondary circuit. Remembering that the primary still has a constant current forced

through it, the same law will hold, the secondary current will remain substantially the same as before, but owing to the external resistance of the circuit, the secondary voltage must therefore be largely increased in order that the current shall remain practically unchanged. The law of turns and voltages will still be followed, and therefore the primary voltage will rise also. The difference between primary and secondary magnetizing effect however will be greater than it was before, because in order to produce added voltage, there must be increased flux in the core and therefore a greater difference between the primary and secondary magnetizing effects.

If the secondary current is open-circuited, the primary current will be maintained unaltered by the generating source and uncounteracted by any secondary demagnetization, for the secondary circuit is open. Therefore the flux in the core will rise to a very high value indeed, causing such a high back electro motive force in the primary coil, that the generator will find it necessary to impress a correspondingly greater electro motive force on the transformer in order to maintain the constant primary current. In short, the transformer will behave very like a direct current series arc dynamo and should be so handled, being short-circuited on no load and whenever load is inserted, it should be open-circuited into the line in the same way as with series arc lamp circuits, and the transformer secondary should never be open-circuited.

In the constant potential transformer it will have been observed that the core flux remains moderately constant, and that the current in the primary and

secondary coils varies according to the exigencies of the load. In the case of the series transformer however, the current in the coils remains constant

FIG. 6.

and the magnetizing flux varies from a small amount on short circuit to approximate saturation on open circuit. Thus for series work a transformer must be designed with careful regard for its iron losses

and its magnetic circuit must be so proportioned as to comfortably carry the maximum magnetic flux, which will appear in the circuit when the largest external secondary resistance that the transformer is intended to supply is connected thereto. The copper of such a transformer, however, need only be

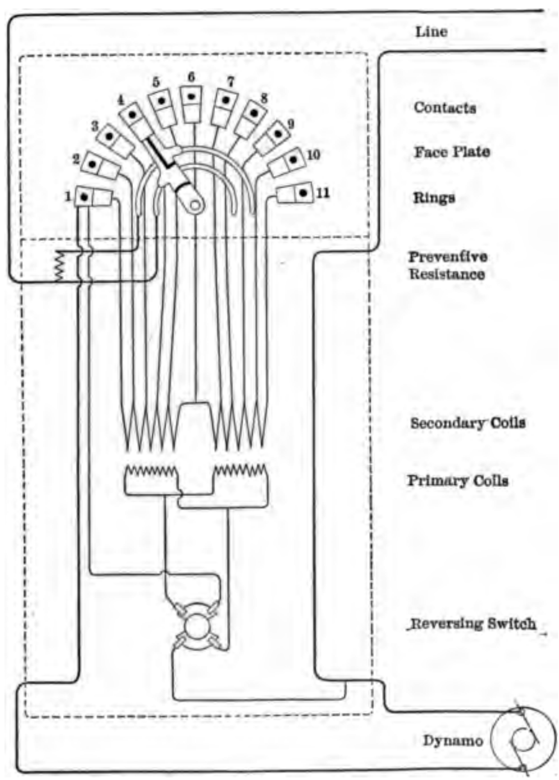


FIG. 7.

INTERNAL CONNECTIONS OF STILLWELL REGULATOR.

proportioned to carry comfortably the constant current at which it is intended to operate. In these respects therefore its design differs from the design of the constant potential type. Series transformers are not much used in practice except in special cases which will be cited farther on. A system of series transformers which are commonly used for arc lighting purposes is shown in diagram in Fig. 1.

In this connection it is interesting to consider a transformer which will generate a constant current of the character required to supply such a system as this. If a transformer is so built that all the magnetic lines of force generated by the primary fail to pass through the secondary, the law of voltages will no longer hold. This fact is taken advantage of in the construction of transformers adapted to be fed at constant potential but required to deliver a constant current. Such a transformer is shown in diagram in Fig. 2. It will be noticed that the magnetic circuit does not closely surround the coils, and therefore if the secondary be placed in a position distant from the primary, there will be a considerable amount of magnetizing flux generated by the latter which fails to pass through the former. Consequently the secondary voltage can be varied by varying its distance from the primary so as to include more or less lines.

If a simple straight core of iron wires be magnetized by alternating current, and a closed secondary in the form of a ring be slipped upon this core as shown in Fig. 3, it will be found that the ring is violently repelled from the exciter coil, and if properly designed the ring may be made to jump several

feet in the air at the instant the primary current is applied. This may be readily explained when it is remembered that the current in the secondary closed

FIG. 8.

THE STILLWELL REGULATOR.

circuit ring is almost equal and opposite in its magnetizing effect to that of the primary, and opposite currents in two adjacent wires cause magnetic re-

pulsion between them. Therefore in such a transformer as the one under consideration, there will be a repulsion between the primary and secondary coils, and if the transformer is ingeniously designed and the secondary held in a position of suspension by a system of chains and counter-weights, this repellant force can be used with advantage for regulating purposes. For this work the system is so designed that a very slight force will suffice to move the secondary to the limit of its travel in its endeavors

FIG. 9.

to increase its distance from the primary, and hence a very slight increase of current will suffice to make it travel the full distance. By proper design the transformer can be so arranged that on short circuit or light load the secondary will be repelled to the

limit of its motion and will produce a certain current. If added load in the form of extra resistance is placed in the secondary circuit, the current will diminish if the secondary retains its extreme position. The effect of this diminished current is to cause the secondary coil to sink into a stronger

FIG. 10.

field, thereby enabling it to raise its voltage and force through the secondary circuit almost as much current as there was before, and for all practical purposes the same current. Such a transformer will therefore give constant current at all loads within the limit of its capacity, its voltage falling as the secondary coil rises and vice versa.

The exact mechanical arrangement of transformers on this principle varies somewhat, the sim-

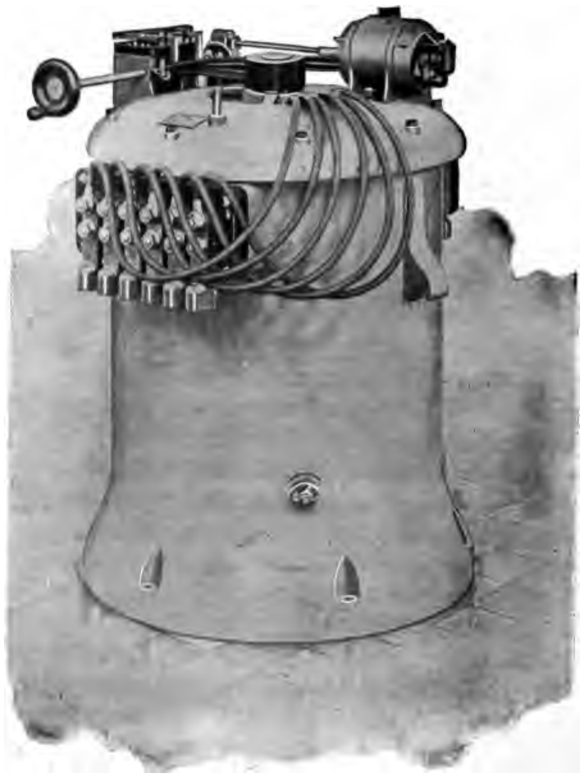


FIG. II.

plest form being shown in Fig. 4. An interesting variation is shown in Fig. 5. This is the case of large transformers where the repulsion of the

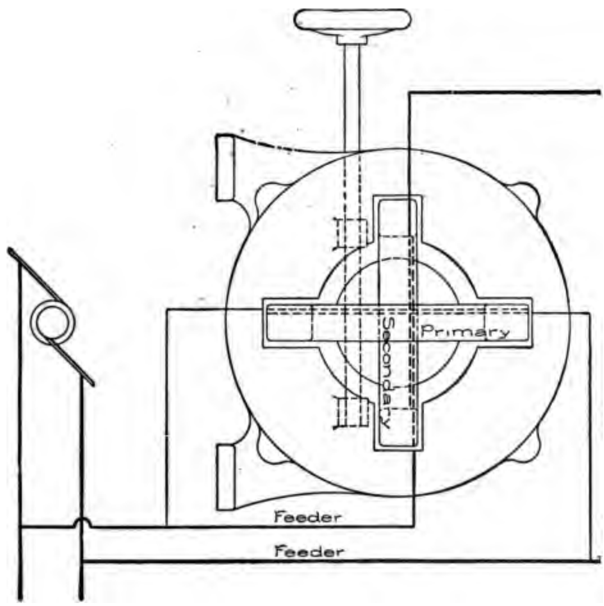


FIG. 12.

secondary, instead of being balanced by a weight, is balanced against the weight of another secondary, the difference being made up by weights. The balancing weights in all cases are equipped with a sector winding up a chain on which the weight is suspended, the sector being so shaped that the balancing force impressed upon the lever varies in the

FIG. 13.

FIG. 14.

same way as the repelling force of the coils. Such a transformer is shown in Fig. 5, the complete machine being shown in Fig. 6. These transformers are sometimes called tub transformers owing to a fancied resemblance of the early forms. They are often oil insulated.

Another interesting application of the transformer is known as the Stillwell regulator. In this arrange-

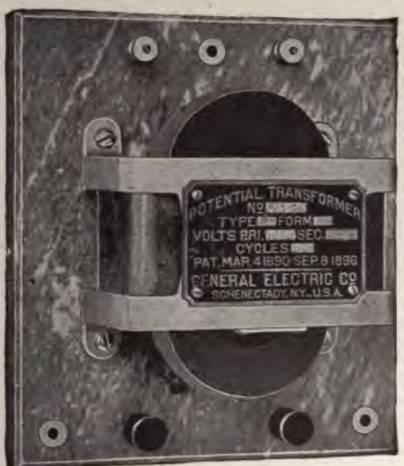


FIG. 15.

ment energy is supplied from a coil in parallel with the primary circuit, and a secondary capable of carrying the full generator current receives energy from this primary, and by reason of its connection in series with the generator circuit, adds to or takes from the line voltage according to connection. This

secondary is commonly made adjustable and reversible also with reference to the primary mains so that it can either add to or take from the primary voltage any part of its electro motive force as far as the range of adjustments will permit. Fig. 7 illustrates the principle and Fig. 8 an actual Stillwell regulator.

Another and very interesting form of transformer is utilized for the same purpose. In this case the secondary is mounted on a movable core which can be revolved with reference to the primary core.

FIG. 16.

When this coil is set so as to register accurately with the primary coil, the full voltage is available and may be added to the primary electro motive force. As the core is revolved, less and less lines from the primary thread through the secondary, and finally at a middle position the secondary contributes no regulating voltage to the lines. Revolving further, it begins to subtract its voltage from the

line voltage as the lines of force are now threading through the secondary in reverse direction and this can be continued up to the limit of the range of the device. This arrangement has the advantage of having no step by step contacts and is therefore capable of infinite variation between its limits and moreover, avoids the arcs at the contacts which are in some cases objectionable. Figures 9, 10 and 11 show the parts and complete assembly of a device of this character.

Still another form of feeder regulator employs both primary and secondary coils which are stationary, and a portion of the magnetic circuit is made rotatable so that it will by proper changes in its position, cause a greater or less number of lines of force from the primary pass through the secondary, thereby varying the voltage which the secondary adds to the line.

Fig. 12 shows how such an apparatus is connected into the circuit, and Fig. 13 illustrates the apparatus itself.

Another form of regulating device employing the transformer principle is shown in Fig. 14. In this case the secondary is a closed ring and is movable with reference to the primary. When directly surrounding the primary the demagnetizing action is so great that much current flows in the primary. When it is moved away on another part of the core the demagnetizing action is reduced and the primary requires more voltage to maintain its current. This primary being in series with the load can thus absorb any desired amount of the generator voltage up to the limits of the device. At the extreme maximum

current position the apparatus is arranged to short circuit itself and thus cut out of circuit. These regulators are used mostly for dimming lamp circuits and are not generally employed to so regulate circuits where a small but constant percentage regulation is desired.

Transformers are largely used to deflect instruments for the purpose of measuring current and voltage. For instance, let us suppose that it is desired to measure a voltage on a 10,000 volt circuit. It would be very inconvenient to construct an instrument to receive and measure this voltage directly, and so for this purpose a small transformer is built which reduces the voltage one one-hundredth in exact proportion, however it may vary, and due correction may be made for this reduction in calibrating the instrument, the load on the latter transformer being so light that the law of voltages and turns is followed very closely indeed and sufficiently accurate for switch board work. Sometimes it is desirable to make the switch board transformer reduce from the primary voltage to the secondary delivery voltage at distant points of the line, and no account is taken of the fact that the primary voltage is thus stepped down, the manipulator being content to adjust his apparatus with reference to the receiver circuit voltage which is after all the most important quantity. In this connection may be mentioned a common but reprehensible practice of loading the voltmeter transformer with pilot lights for switch board purposes, it usually being very convenient to run wires thereto. A loaded transformer as we have een, does not follow the law of voltages and turns

as closely as one which has practically no load and therefore the accuracy of the indications of the instrument are seriously affected by this practice. A switch board transformer is illustrated in Fig. 15.

For measuring heavy alternating currents a series transformer is employed. This series transformer rarely has an iron circuit because the flux in this transformer varies and the quality of the iron would throw variations in the indications of the instrument connected to the secondary. With an air core the number of lines of force threading through the primary and secondary is directly proportional to the current in the primary provided very little current is taken from the secondary. Therefore the secondary voltage is directly proportioned to the flux and to the current, and can be measured by a suitable instrument and calibrated in amperes. A series transformer for this purpose is shown in Fig. 16.

CHAPTER V.

PHASE DIFFERENCE AND VECTOR SUMMATION.

When alternating currents or electromotive forces are not in step, they are said to differ in phase. It can be easily seen that this phase displacement may be any amount from the exact opposition to exact agreement. The amount of phase displacement is measured in degrees. The degree as a unit is chosen for this purpose because it is very convenient in calculation, as we shall see later on, and particularly in a certain process invaluable in alternating current work known as vector summation.

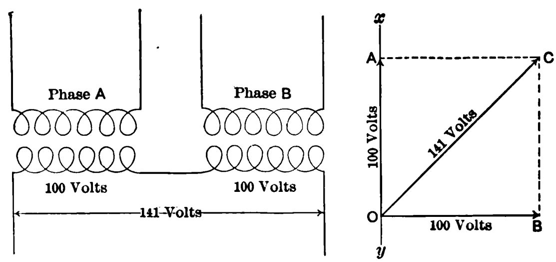


FIG. I.

If we connect two alternate electromotive forces in series and they agree in phase, the potential at the free terminals of the circuit will be equal to their simple arithmetical sum as in the case of direct currents. If, however, the alternate electro motive forces differ in phase, the terminal potential will not be their simple sum, but a quantity differing therefrom according to the amount of phase shifting be-

tween the two component electro motive forces which combine to produce the resultant. It is for these cases that the simple process of vector summation has been devised.

It is highly important that this principle be thoroughly mastered by the student especially in polyphase work where it is often necessary to combine currents or electro motive forces which differ in phase and to determine the magnitude and phase of the resultant.

In vector summation we will first consider the case of electro motive forces. We will suppose that

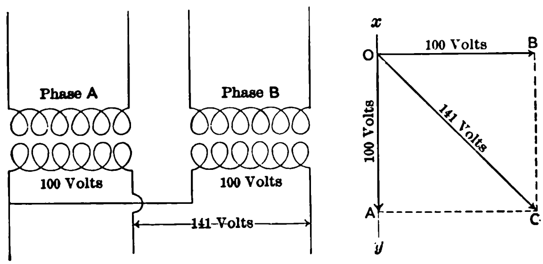


FIG. 2.

we have two electro motive forces each from a separate transformer excited from the two phases of a two phase machine. These electro motive forces will not be in step but will be held rigidly 90° apart, by the machine. One electro motive force will be a maximum, while the other is zero and vice versa. What will be the magnitude and phase of the resultant if these electro motive forces are connected in series?

Figure 1 shows the circuit connections, and at the right thereof is a vector diagram which solves the

problem. In this diagram the electromotive force of 100 volts from the transformer supplied from phase A is represented by the line O A which is 100 units in length. Its phase is represented by the angle it makes with the vertical reference line x y, and in this case it happens to coincide with it. The electro motive force from the transformer supplied from phase B is 90° behind that of phase A, and is therefore represented by line O B, also 100 units long, but 90° behind O A or at right angles thereto. The convenience of using the degree notation now becomes apparent. The resultant, which it is the ob-

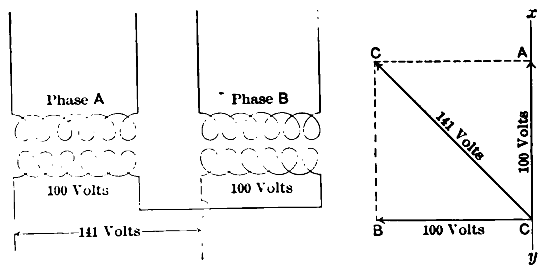


FIG. 3.

ject of the problem to find, is represented in magnitude and phase by the *diagonal of the completed rectangle.* If the drawing is carefully laid out to scale it will be found to be 141 units or volts long, 45 degrees behind O A and an equal amount ahead of O B. 1.41 is the square root of two and is always the ratio between the resultant and its components if the latter are equal and 90° apart. As this is a common combination in two phase work it is important to remember this ratio.

If one of the electro motive forces be reversed, the combination in figure 2 is obtained. A moment's inspection shows that the resultant O C is of the same magnitude as it was before, but its phase position has been shifted back 90° from the former position. It is now 45° *behind* instead of ahead of O B, counting counter clockwise. If phase B is reversed instead of phase A, we get the result shown in figure 3. The resultant is unchanged in magnitude but altered in direction, being now 45° ahead of O A and 90° ahead of its original position.

Finally if both A and B are reversed, that is to say their free terminals are applied to the receiver circuit in reversed relation, the arrangement shown in figure 4 is obtained. O C the resultant is still unchanged in magnitude but changed in position,

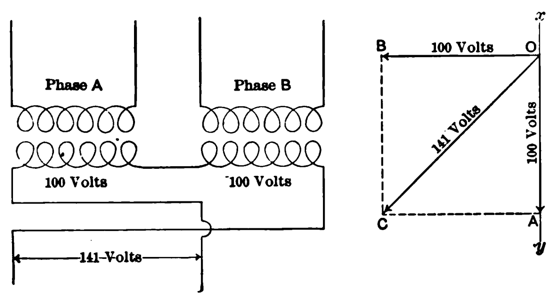


FIG. 4.

in fact 180 degrees removed from its position in figure 1.

From the foregoing we have the following important results:

1—A resultant of two combined electromotive forces is the diagonal of their completed parallel-

ogram on a vector diagram, and is thus represented in both magnitude and phase relation.

2—A resultant combined of two equal electro motive forces 90° apart are equal to one component multiplied by the square root of two and is exactly midway between them.

3—Reversing an electro motive force is equivalent to shifting it 180 degrees on the vector diagram.

We are now ready to investigate a more complicated case shown in Fig. 5. In this case the components are not equal and the diagonal O C, while the diagonal of the parallelogram as before, is nearer in phase to the more powerful component. By

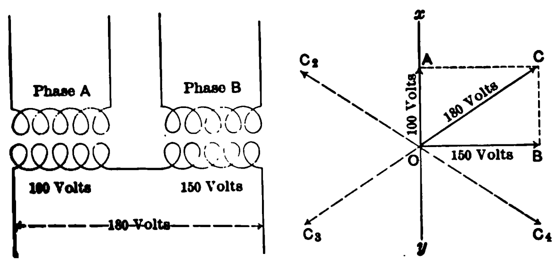


FIG. 5.

versing the electro motive forces relatively to each her and to the receiver circuit, the magnitude of ie resultant would remain unchanged, but it could be made to occupy any one of the positions, O C_1, OC_2, OC_3, OC_4.

We are now ready for another important rule. When the electro motive forces 90° apart are connected in series, the *magnitude* of the resultant is ot changed however the electro motive forces are

connected together. The phase position of the resultant can, however, be shifted in four different positions by changing the connections.

When the component forces are at some other angle than 90°, the case is altered. In machines

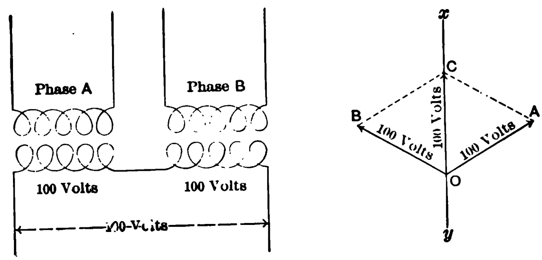


FIG. 6.

giving three electro motive forces displaced in phase, the forces are 120° apart.

If we take two electro motive forces of the three from a three phase machine and connect them in series, we shall have combinations as follows:

Figure 6 shows the connections and vector diagram of two equal forces 120° apart. OC the resultant is the diagonal as before and will be found to be equal to either of the components and midway between them in phase as will be found if a drawing is made to scale.

If, however, O A is reversed thereby and moved 180 degrees on the diagram, the results shown in figure 7 are found. OC the resultant is shifted 90° and increased in value to 173 or one hundred times the square root of three. This is a common ratio

in three phase combinations and should be remembered. It will be seen at once by shifting the connections as described in preceding paragraphs that the resultant can be given two values and four phase positions as shown in figure 7.

Finally let us take the case of several displaced electro motive forces to be connected in series. The

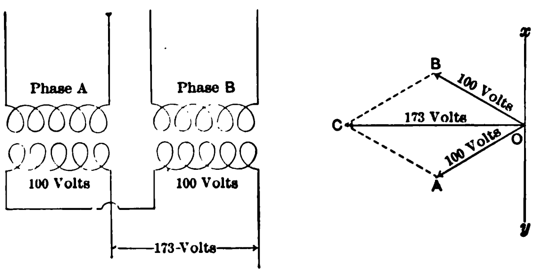


FIG. 7.

case is depicted in figure 9. OA and OB are first combined to form OB in the manner described, and OB is combined with OC, the remaining electro motive force, to form the final resultant OE. Thus the process can be extended and carried into endless combinations.

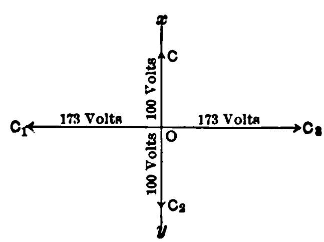


FIG. 8.

The attention of the student is earnestly recommended to the foregoing, for by its aid many puzzling problems may be solved. The *resultant* electro motive force in a complete circuit is a very important matter to determine for the current flows in accordance with it, agreeing with it in phase and pro-

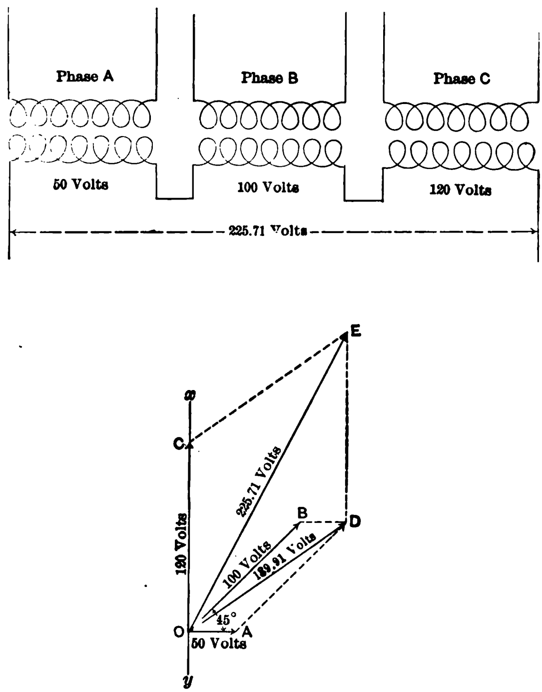


FIG. 9.

portional to it in magnitude according to the time-honored Ohm's law.

CHAPTER VI.

Phase Difference and Vector Summation—Continued.

In the last chapter a few notes were given concerning the study of combining voltages of different phase and obtaining the resultant voltage. In polyphase work it very frequently happens that *currents* of different phase add together in a common line and the resulting current differs in phase and

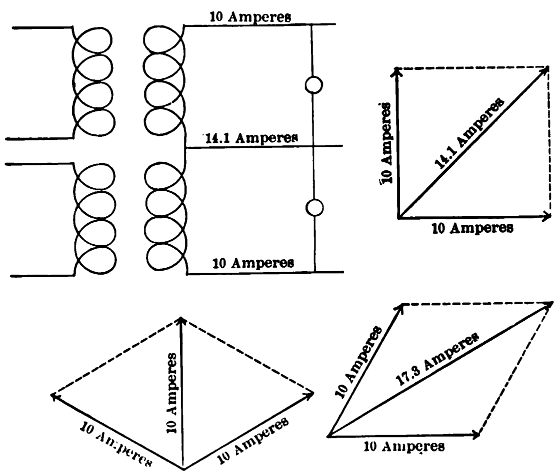


Fig. 1.

magnitude from that which would obtain in the ordinary combination of direct currents. For instance, if we had two transformers as shown in Fig. 1 and these transformers were alike in voltage

and current capacity and excited at the same phase we could arrange a three wire system from them as shown in the figure. This three wire system would have all the properties of a direct current three wire system and as long as the load was balanced there would be no current in the middle or neutral wire, and the amount that the neutral would carry would depend upon the unbalancing of the load. If however the phases of the currents in the two transformers are shifted and held in a rigidly shifted position by suitable means such as exciting the primaries from the current of different phases obtained from a polyphase generator, the current in the neutral wire requires to be determined vectorially.

Let us take first the case where transformers A and B produce currents which are shifted 90 de-

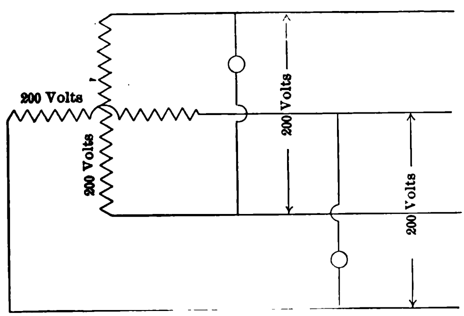


FIG. 2.

grees with relation to each other. Let us assume that the loads on each transformer are the same, namely 10 amperes on each transformer. What is the phase and magnitude of the current in the neutral wire? It is best in such a case to consider that

the neutral wire is a common return for the transformer, and that whatever current enters it at its distant end to flow back to the transformer system, combines vectorially with the other currents. In

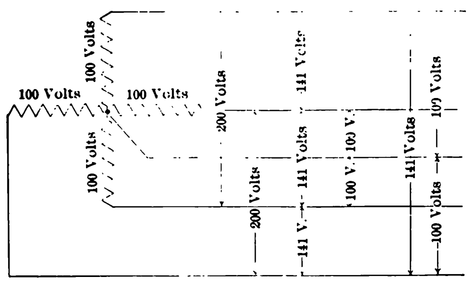


FIG. 3.

this case the vector diagram at the right of Fig. 1 solves the problem. The current in the neutral wire it will be seen is 14.1 or ten times the square root of 2, and is shifted in phase midway between the phases of the currents in the two outer wires. This is called the three wire two phase system and is quite an important system.

If the two transformers were excited from two of the phases of a three phase machine, the voltages being 120 degrees apart, the resulting current in the middle wire would agree in magnitude with those in the outer wires, but would be shifted midway between them in phase, the vector diagram at the right of the figure being the geometric solution of the problem. If the phases were 60 degrees apart, the current in the middle wire as shown by the vector diagrams in the lower part of Fig. 1 would be 17.3,

or ten times the square root of 3. These current and voltage combinations that have been given will be found exceedingly useful in the polyphase combinations which are now to be studied.

A polyphase machine is one which is capable of giving two or more currents from its windings which are rigidly fixed in shifted phase relation to each

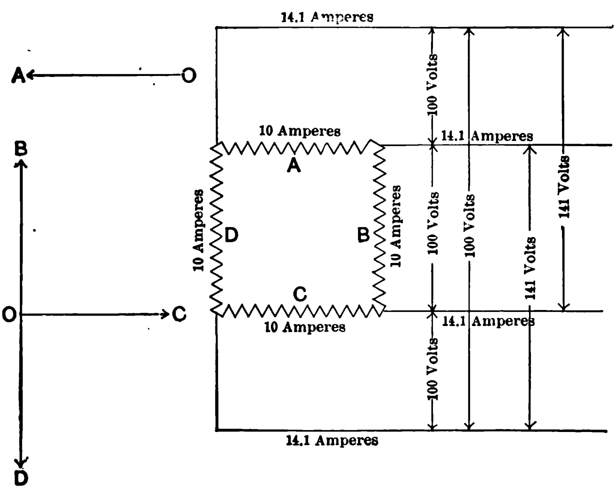


FIG. 4.

other. The details of construction of such a machine are left for succeeding chapters. It is sufficient for the student to remember that such machines present to the circuit several terminals between each of which is a winding located on the armature of the machine, and that the voltage obtained between each of the terminals and the phase differs in different cases. For instance we may have a two

phase machine which is equipped with two independent windings so arranged on the armature that they produce voltages 90 degrees apart. Such a machine would have four terminals, two for each independent circuit. It is commonly represented by the diagram shown in Fig. 2, and is called the two phase four wire system. Each circuit is loaded independently of its mate as a simple alternating current circuit, and thus single phase work can be had from such a machine. Wherever motors or other devices requiring both phases are necessary, all four wires are led to the locality and current is taken from the four wires simultaneously. It will be noted that the coils representing the windings on the armature are at right angles to each other in the diagram. This is a very common way of illustrating two phase windings, the right angled arrangement of the coils being suggestive of the fact that the currents in them are 90 degrees apart.

Sometimes the two phase machine is wound in the same way as previously described, but the middle points of both windings are connected together in a neutral point and a wire is brought therefrom. This forms the two phase five wire system which is useful in some cases. A winding connected in this way is called a star winding. The voltages obtaining between these wires now require some explanation. If the voltage of each complete coil from the centre winding out to the free terminal is 100 as indicated on the diagram, the voltage between any two adjacent free terminals, as it includes two coils of different phase, will be 100 times the square root of 2 or 141. The voltage between diagonally opposite

terminals on the diagram will be the sum of two voltages agreeing in phase, or 200, while the voltage between any one terminal and the middle wire will be 100. Thus it will be seen that a plurality

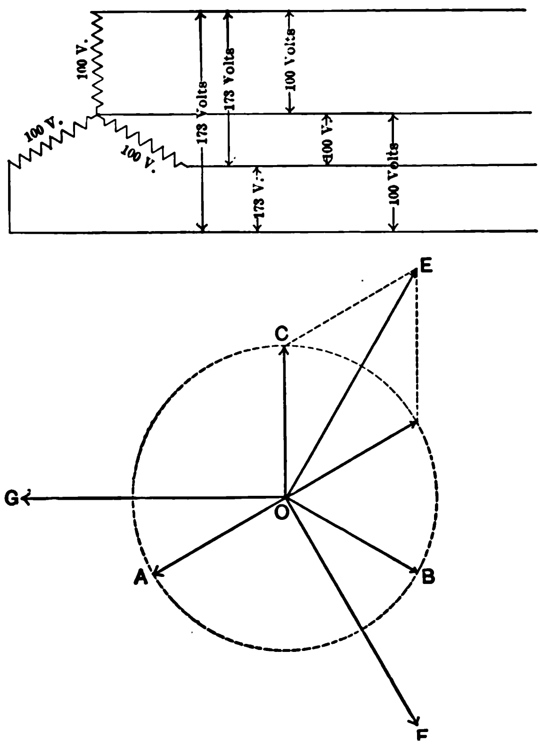


FIG. 5.

of voltages can be obtained from the same machine, and moreover by selecting any two adjacent terminals, four equal voltages can be obtained which differ from each other by 90 degrees. See Fig. 3.

Sometimes the two phase generator is equipped with four coils each giving a voltage 90 degrees removed from that of its neighbor. The terminals of these coils might be laid out independently forming 8 wires leading from the machine but it is more common to connect the coils together as shown in Fig. 4. This combination is called the mesh combination. It will be seen at once that connecting four coils together in this way will not cause the coils to exchange currents among themselves, for if we consider coil A to have an electro motive force

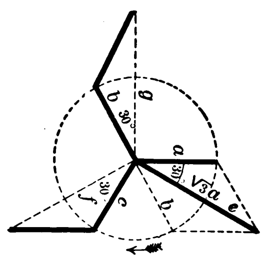


FIG. 6.

shown by the line O A in the diagram at the right of the figure, and add together vectorially the voltages of the three other coils, as shown in the lower diagram, we shall have as a resultant the electro motive force O C, for O B and O D neutralize each other in the combination of the three, therefore the terminals to which O A is connected present an exactly equal and opposite force and consequently currents cannot be exchanged between e coils in the system. Therefore we may lead out wires from each corner or connecting point of

the four coils, and obtain a four wire two phase system which is interconnected, the voltages between any two adjacent wires will be, according to diagram, 100 volts, and equally spaced in phase 90 degrees apart around the circle. The voltages between two opposite terminals combining as they do two 100 volt circuits differing 90 degrees in phase, will of course be 141. The current in each of the coils of the machine is given as 100 amperes, but the current in each outgoing wire receiving the combined currents of two coils differing in phase 90 degrees apart will be 141 amperes by virtue of the previous considerations. This arrangement of connecting coils in a loop is called the mesh principle. It is largely used in polyphase work.

In three phase work we might have a machine with three independent coils presenting these terminals to an outside circuit from each of which might be drawn a current differing 120 degrees from its neighbor. This however is almost never done, the windings being invariably connected on either star or mesh plan. Fig. 5 shows a three phase winding connected on the star plan. The coils are shown 120 degrees apart, being suggestive of the phases that they generate, and three wires are led, one from each terminal and a fourth from the common junction to the receiver circuit. Let us suppose that each coil is generating 100 amperes at 100 volts. The voltage between any two terminals will therefore comprise the voltage of two coils. It is customary in the three phase machine to connect like terminals of the coils to the common junction. This has the effect as is well known of reversing the relation of

the electro motive forces on the vector diagram and hence placing the combining voltages between two adjacent terminals 60 degrees apart. The voltage between them in this case is 173. The current in each coil is of course the same as in the line to which it is connected. The voltage between any outer wire and the system and the common centre wire is of course the same as the voltage of the coil connected be-

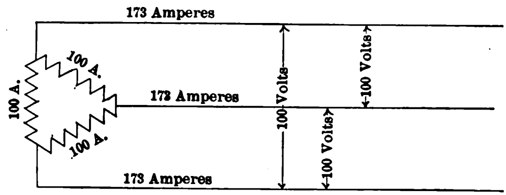


FIG. 7.

tween these points, namely, 100. The vector diagram shown in Fig. 6 shows a valuable feature of this arrangement. The three voltages generated by the coil are shown by the heavy lines marked *a b c*, and between the neutral wire and the three terminals these three voltages can be obtained. The three voltages obtained between the three outer wires, 173 volts each, are shown by the lighter lines *e f g*, 30 degrees removed from the original voltages, the vector combination being shown by the triangle, in which it will be noted that one of the components is reversed on account of the connection employed in the machine. If the voltages obtained from a poly-se machine are reversed by means of trans-rs, duplicate voltage 180° removed therefrom

will be obtained. If this is applied to the three phase machine, six different phases will thereby be produced. Combinations of this character are used in rotary converter work. This system of connecting three phase coils is sometimes called the Gamma or Y system, because of the fancied resemblance of the diagrams illustrating it to the Greek letter Gamma or the English capital Y.

Another system which is largely employed in three phase work connects its three coils on the mesh plan, Fig. 7. A consideration of this arrangement by the aid of a vector diagram shows that between two points on the system to which a coil is connected there exists an equal and opposite electro motive force due to the other two coils, hence such a system will not exchange currents within itself. This system is sometimes called the Delta on account of the resemblance of the diagram to the Greek letter. From the corners of the Delta are led three wires to the receiver circuits. Between any of these three wires exists an electro motive force equal, and agreeing in phase with that of the coil connected between them. In the case of the diagram this electro motive force is 100 volts. If the current in each coil is 100 amperes, the current in the line will be found to be 173 amperes because it is the combined current proceeding from two coils differing in phase from one another. Receiver circuits such as transformers, rotary converters, and the like are largely connected on the Delta plan, while generators more frequently resort to the Y combination although both arrangements are used.

Sometimes a combination of the Y and mesh sys-

tem are employed, as shown in Fig. 8. This, how-

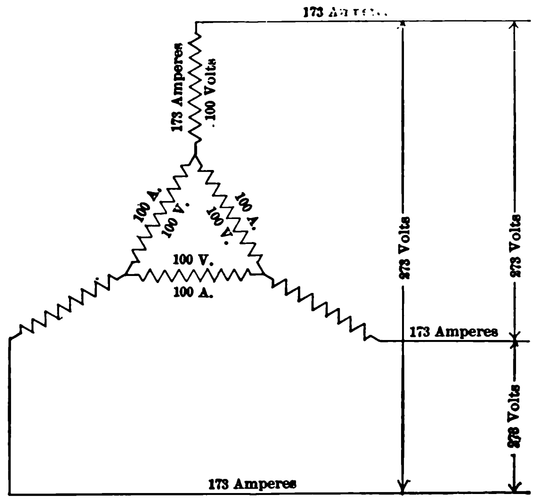


FIG. 8.

ever, is a possible combination of academic interest and is not much used in practice.

CHAPTER VII.

Copper Calculations for Polyphase Circuits.

Polyphase generators are used most largely because of the fact that polyphase currents are more readily adapted to driving motors than single phase current. An additional inducement is due to the fact that copper economy is obtained by means of utilizing polyphase systems, and particularly is this true of the three phase system. A four wire two phase system obviously is equivalent to two single phase systems and effects no economy of copper in transmitting the power over the ordinary two wire plan, but in other combinations of polyphase currents a copper economy appears.

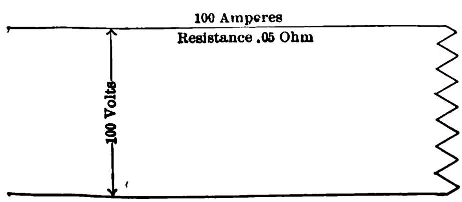
Let us consider a standard problem of 10 kilowatts to be transmitted and delivered net at the receiver circuit with a watt loss of 10 per ct. in the line. Let us further assume that the transmission voltage at the receiver end is to be 100. Here arises a difficulty which is a stumbling block for many students of this problem. Some polyphase systems, as we have already seen, present a plurality of voltages. Which of these voltages is to be considered as the transmission voltage? "If the transmission voltage is taken as that of the receiver circuit and if the polyphase system consists of as many independent circuits as phases, there is no saving of copper by the employment of polyphase currents, for each system could be considered as a group of so many single phase systems.

In some cases, the transmission voltage is considered as that between which the load at the distant end is connected. This process of reasoning will now be applied to the following systems.

Case A. The single phase system.
" B. The two phase independent winding system.
" C. Two phase mesh system.
" D. Two phase five wire system.
" E. Three phase Y system.
" F. Three phase Delta system.
" G. Two phase three wire system.

In case A the current generated in the coil of the dynamo must be 100 amperes, the voltage generated must be 110, and the resistance of each line must be $\frac{5}{100}$ = .05 ohm, as the total drop in the line is 10 volts and the loss 1 kilowatt.

BASIS, TRANSMISSION VOLTAGE THE VOLTAGE AT WHICH THE POWER IS UTILIZED.



Case A Copper 100

On the two phase independent system for equal energy, see case B each of the independent ·cuits at the receiver end must receive 50 amperes ·) volts or 5 kilowatts each. The loss in each · must not exceed ¼ of a kilowatt, and as

each is carrying 50 amperes, the voltage lost must be 5 in each line, and the resistance of each line must therefore be .1 of an ohm. Hence we have twice as much wire as before of double the resistance and therefore the same amount of copper.

The next case C, is that of the four wire two phase mesh system. Here we receive four currents of 25 amperes each to make up the quota of 10 k. w. The current in each line wire is 25 $\sqrt{2}$ and the energy lost in each wire is ¼ k. w., hence the volts lost in each wire must be

$$V = \frac{250}{25\sqrt{2}} = \frac{10}{\sqrt{2}}$$

The resistance of each wire is therefore

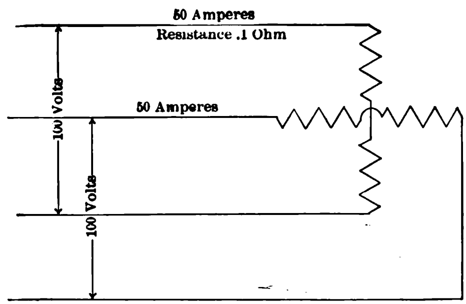
$$R = \frac{\frac{10}{\sqrt{2}}}{25\sqrt{2}} = \frac{10}{50} = .2 \text{ ohm}$$

double the resistance of the two phase independent circuit system and therefore using half the copper. It will be noted, however, that in this combination, there exists a voltage higher than that assumed to be the voltage of transmission, namely, the voltage between opposite corners of the mesh.

The two phase star system, which is the next problem D, has five wires. If the loads are balanced it will be seen that application of the vector diagram to determine the current in the middle wire will show that for every current entering it there is an equal and opposite current leaving it. Hence this wire carries no current when the loads are balanced, and

is extra copper to be fixed by the amount of unbalancing to be expected, and in a balanced system need not be considered. The voltage around any one of the receiver coils is $\frac{100}{2}$. The current therefore must be 2.5 k. w., divided by the volts

$$C = \frac{2500}{\frac{100}{2}} = \frac{5000}{100} = 50$$



Case B Copper 100

Hence the current and copper conditions are exactly the same as in the case B, plus whatever is invested in the central balance wire.

The next case E, is that of the three phase Y system. Here we have three receiver coils. The voltage around each receiver coil is $\frac{100}{\sqrt{3}}$. Each receiver circuit absorbs 3333-1/3 watts. Hence the current is

$$C = \frac{\frac{3333\frac{1}{3}}{100}}{\sqrt{3}} = 33\tfrac{1}{3}\sqrt{3}$$

Each line wire absorbs 333-1/3 watts. Hence the line drop per wire is

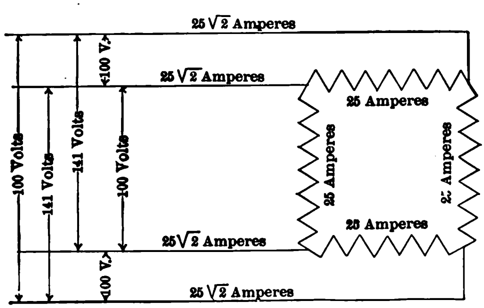
$$\frac{333\frac{1}{3}}{33\frac{1}{3}\sqrt{3}} = \frac{10}{\sqrt{3}}$$

and the resistance of each line wire is

$$\frac{\frac{10}{\sqrt{3}}}{33\frac{1}{3}\sqrt{3}} = \frac{10}{100} = .1$$

Hence we have three lines each of .1 ohm. The conductivity of each line is therefore 10 and of all three 30. With the single phase system the conductivity of each line is $\frac{1}{.05} = 20$, and of both lines is 40. Hence the three phase system requires only 75 per cent. of the copper needed for a single phase system, other things being equal.

With the mesh system F of Delta plan the same



Case O Copper 50

copper economy obtains by a little different reason-

ing. Each receiver circuit gets 33-1/3 amperes at 100 volts. The line current is therefore 33-1/3 $\sqrt{3}$. The line loss per line is 333-1/3 watts. The volts lost per line is

$$\frac{333\frac{1}{3}}{33\frac{1}{3}\sqrt{3}} = \frac{10}{\sqrt{3}}$$

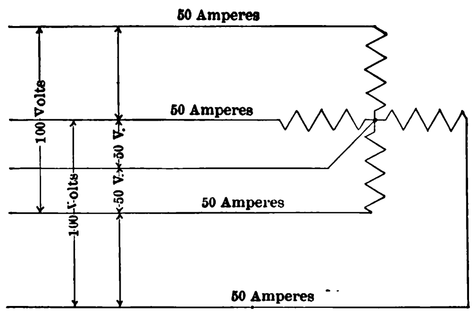
The resistance of each line is

$$\frac{\frac{10}{\sqrt{3}}}{33\frac{1}{3}\sqrt{3}} = \frac{10}{100} = .1$$

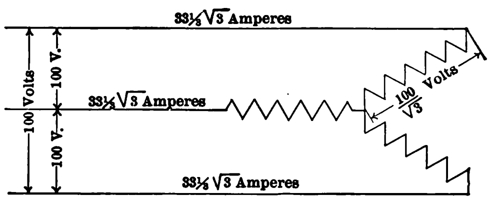
as before and the same copper economy obtains. With the three phase four wire system the balance wire carries no current with balanced load as the vector diagram will show, and therefore simply represents an extra copper investment fixed according to the operator's judgment.

A case somewhat more puzzling to compute is that of the two phase three wire system shown in G, Fig. 1. In this case the receiver coils get their voltage of 100 as per the original assumption and throw their combined current into the middle common return wire. There are two coils. Each absorb 5 k. w. or 50 amperes at 100 volts. The current in the middle wire is 50 times the square root of 2 amperes, the resultant of the two two phase currents. If the loss is divided equally between the three wires, each of the two wires absorbs one-third of a kilowatt, 333-1/3. The volts lost in each of the two outside wires is therefore

$$V = \frac{333\frac{1}{3}}{50}$$

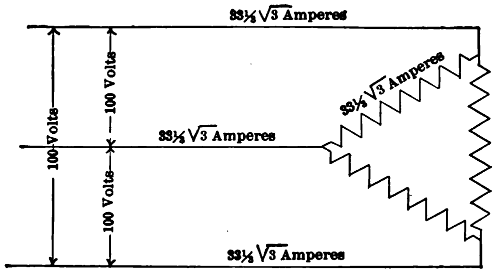


Case D Copper 100+

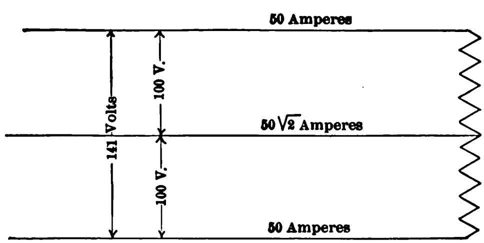


Case E Copper 75

FIG. 1.



Case F Copper 75



Case G Copper 75

FIG. 1. (CONTINUED).

and the resistance of each of the two outside wires is

$$R = \frac{V}{C} = \frac{\frac{333\frac{1}{3}}{50}}{50} = \frac{333\frac{1}{3}}{2500} = .1333 \text{ ohms.}$$

There are two of these wires. The middle wire absorbs one third of a kilowatt also but it carries 50 times the square root of 2 amperes. The volts lost is therefore

$$V = \frac{333\frac{1}{3}}{50\sqrt{2}}$$

the resistance of this wire is

$$R = \frac{V}{C} = \frac{\frac{333\frac{1}{3}}{50\sqrt{2}}}{50\sqrt{2}} = \frac{333\frac{1}{3}}{5000} = .06667$$

the conductivity of one of the outside wires is equal to

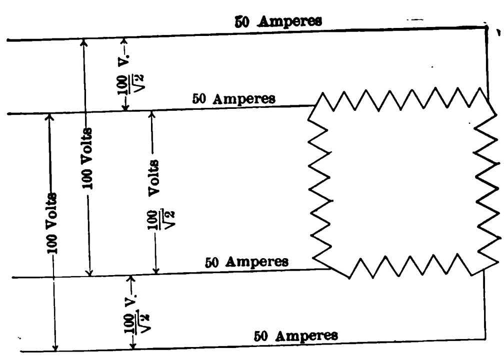
$$K = \frac{1}{.133} = 7.5$$

and of both of the outside wires the conductivity is therefore equal to 15. The conductivity of the middle wire is also 15, and therefore the conductivity of all three wires is 30. We have found in a previous paragraph that the conductivity of the single phase line wires in this standard problem is 40. Therefore considering the problem in this form, the saving in copper due to a two phase three wire system is 25 per cent.

There are, however, other methods of looking

at the problem of polyphase copper economy. Some engineers prefer to consider the voltage of transmission as the highest voltage to be found in the system. They equate the difficulties of insulation against each other. This gives somewhat different results in those cases that have been discussed where a higher voltage is to be found than that which has been assumed to be the voltage of transmission. In Fig. 1, cases A, B D E and F figure out the same as before because in none of these cases does there exist a voltage higher than that assumed to be the voltage of transmission. Cases C and G, however, show higher voltages than 100. Case C shows a voltage of 141 across the corners, and case G shows the same voltage across the extreme outside wires. If we consider the copper economy, assuming the voltage of transmission to be the highest voltage to be found between any wires on the sys-

BASIS, HIGHEST VOLTAGE ASSUMED TO BE TRANSMISSION VOLTAGE



Case C Copper 100

FIG. 2.

tem, these cases must be recomputed. This is shown in Fig. 2, in which case the maximum voltages to be found on the system are fixed at 100. Taking first case C, we have four receiver coils each of which has a voltage of $\frac{100}{\sqrt{2}}$ and each absorbs 2.5 kilowatts. The current in each receiver coil is therefore

$$C = \frac{2500}{\frac{100}{\sqrt{2}}} = 25\sqrt{2}$$

The current in each line wire in this case will then equal $25\sqrt{2}\sqrt{2} = 50$ and the same conditions will occur as in case B, Fig. 1, and no saving in copper will be found.

Taking up case G, Fig. 2, the highest voltage to be found in the system has been fixed at 100. The voltage in each receiver coil is therefore $\frac{100}{\sqrt{2}}$ The current in each receiver coil is therefore

$$C = \frac{5000}{\frac{100}{\sqrt{2}}} = 50\sqrt{2}$$

This is also the current in the two outside line wires. The loss in each outside line wire is 333 1/3 watts. Consequently the volts drop in each outside line wire is

$$V = \frac{333\frac{1}{3}}{50\sqrt{2}}$$

and the resistance of each line wire

$$R = \frac{V}{C} = \frac{\frac{333\frac{1}{3}}{50\sqrt{2}}}{50\sqrt{2}} = \frac{333\frac{1}{3}}{5000} = 0667$$

The middle wire now carries a current equal to $50\sqrt{2} \times \sqrt{2} = 100$. The loss in the middle line wire is one-third of a kilowatt, and consequently the volts lost in the middle wire is

$$V = \frac{333\frac{1}{3}}{100} = 3.33$$

The resistance of the middle wire is therefore

$$R = \frac{V}{C} = \frac{3.33}{100} = 0.0333$$

The conductivity of one of the outside wires is 15. and of two of them is 30. The conductivity of the middle wire is also 30, making the conductivity of all three wires 60. Hence considering the problem in this way the copper economies are as 40 is to 60 in favor of the single phase system, and the copper used is therefore 150.

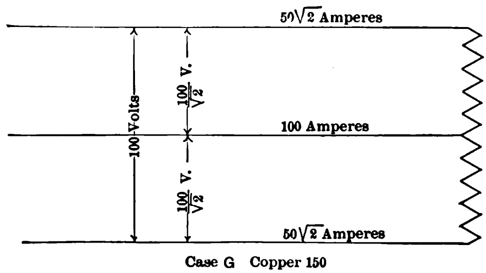


FIG. 2 (CONTINUED).

Reviewing the case as a whole, we see that if we consider as is usual and fairest, the highest voltage to be found on the system as the voltage of transmission, that the only polyphase system that shows a copper economy is the three phase system, which shows a saving of 25 per cent.

That to select any voltage other than the highest existing voltage as the voltage of transmission is manifestly unfair, in comparing the relative merits of systems, can be shown by applying the propositions to the case of direct currents. For instance, in the common three wire system, should the voltage of transmission be selected as the voltage between neutral and one side, it is then very easy to figure that the copper required is only one fourth that required for a two wire system plus whatever it is desired to expend in the neutral. No one, however, credits the three wire system with accomplishing this economy, but rather the fact that a double voltage is used.

CHAPTER VIII.

Copper Calculations—Continued.

In polyphase work, where long distances of transmission are involved, the loss in the line in watts is the important factor, and calculations with reference to the copper to be used are carried out along the line laid down in the preceding chapter. The actual loss in voltage is a secondary consideration, for machinery may be had which will operate successfully at the voltage which may obtain. The variations of voltage at the motor are not serious as compared with variations of voltage at lamp termini. It is, however, important to calculate the line losses with reference to the voltage, especially in local distribution where many lamps are used, and accordingly in this chapter the calculations of copper will be studied from this point of view. These calculations will first be conducted, neglecting the inductive reaction of the line itself, which in short distribution systems, where the currents are light, is not important.

In simple single phase systems the calculations are essentially the same as those of direct currents. The current in the line is determined by e nature of the load desired, and that divided

into the ohmic resistance of the line gives the volts drop, or, if the volts drop is fixed and the current determinate, the resistance can be computed, and from that the dimensions of the line itself. In simple single phase systems it is permissible to calculate the drop of each leg of the line separately and add them together to get the total drop, but this is not permissible in the case of polyphase systems. This is also permissible in the case of two phase independent circuit systems; but in the case of comparing the drop between two wires, in which the currents differ in phase, the drops must be vectorially added with reference to the phase difference known to exist.

Taking a practical example, let us suppose that we have a three phase circuit one thousand feet long, each leg of which is to carry ten amperes, and that we wish to limit the drop in this line to five volts between any two of the three wires; that is to say, if we have 105 volts at the transmission end between any two wires, 100 volts is to appear at the receiver end between any of the two. If we should attack this problem in the same way that we would a single phase problem, and that general procedure would be to give each wire a drop of $2\frac{1}{2}$ volts, the resistance of each leg of the line would be

$$R = \frac{2.5}{10} = .25 \text{ ohms},$$

and the size of the wire would be No. 4 Brown & Sharp. We should find, however, on making measurements with the voltmeter on a line so

constructed, that the total drop, instead of being 5 volts, would be 4.33 volts, or 2.5 multiplied by the square root of 3, for the simple addition of the two drops is not permissible. Therefore, in the three phase circuit, it is necessary so to proportion the drop on one line that when multiplied by the square root of 3 it will give the desired total drop. In other words, we must divide the total drop 5 by 1.73 to get the volts loss in each leg of the line. This figure is 2.88, and the resistance of the line is therefore .288, and the size of wire, instead of being No. 4 Brown & Sharp, is nearer No. 5.

In a two phase system connected on the mesh principle, the drop between adjacent corners of the system will be equal to the sum of the drops in the lines feeding those corners, because those currents are in phase with one another, but the drop between opposite corners of the mesh will not be equal to the simple sum but will be a lesser amount; in fact, it will be equal to the drop in one leg multiplied by the square root of two. Similarly, in the two phase star system, the drop between opposite corners will be equal to the sum of the drops in the individual legs supplying them; but the drop between adjacent corners will be equal to the drop in one leg multiplied by the square root of 2, because phase difference obtains in those two lines. In the case of a polyphase unbalanced system, where one line carried a lagging load and the other a leading load, the phase difference between the currents in the line

must be determined, and the drops placed on a diagram in vectorial relation, according to the phase difference so found, and vectorially added either graphically or by trigonometric calculation.

In the case of a two phase three wire system the same procedure must be followed; but, by reason of the fact that the currents flowing in the central leg are larger than the currents flowing in the two outer legs, it is not sufficient to multiply by the square root of 2; and there is, further, an additional consideration due to the fact that the current in the central leg is not 90° displaced from the current in the outside legs, but is 45° displaced therefrom. The treatment in this case will be best illustrated by a practical problem.

Let us take a case where 10 kilowatts is to be transmitted, and that the voltage of the two phase termini at the generator end of the line is 110 volts, and that the voltage at the receiver end of the line shall be 100. The vector diagram will show two equal lines at right angles to each other, which represent the currents in the outside legs. In the common return leg the current will be represented by the diagonal of the square so formed, and will bear to the outside legs the relation of 1.41, as shown in Fig. 1. If the wires are all three of the same size, the drops will be proportional to the currents they carry, and will occupy the same vectorial relation. Combining them as shown by the lighter lines, the condition is that the two resultants must each be equal to 19. In order that the conditions of the problem

shall be fulfilled, and knowing these longer lines to be 10, we must calculate backward by trigono-

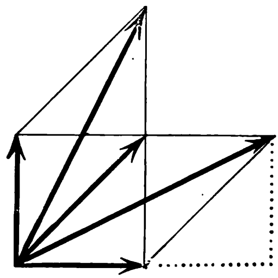


FIG. 1. VECTOR DIAGRAM OF TWO PHASE THREE WIRE SYSTEM ILLUSTRATING DROPS.

metrical means to find out what the drop in each individual line will be. An examination of the geometry of the diagram will show that the resultant drop 10 is equal to the square root of the sum of the squares of the drop in one outside leg, and the double of that amount. The dotted portion of the diagram, which forms a right-angle triangle with reference to one of the resultant lines, will assist in showing that this is true. That is to say,

$$10 = \sqrt{x^2 + 4x^2}$$

$$= x\sqrt{5},$$

whence

$$x = \frac{10}{\sqrt{5}}$$

$$= 4.472,$$

and multiplying by the square root of two we get the drop in the centre line or common return 6.323.

As the centre wire in a two phase three wire system carries nearly 50% more current than the two outside lines, it is not common to make this wire of the same size as the three outgoing wires, but more common to make it of such a size that the ohmic drop around its terminals shall be the same as that in the two outside legs, that is to say, the current density in all three wires shall be the same. In such cases the diagram representing the situation would be constructed a little differently; and as it is illustrative of the method of handling the problem, no matter what the size of wire is concerned, it will be discussed here. This diagram is shown in Fig. 2, and the

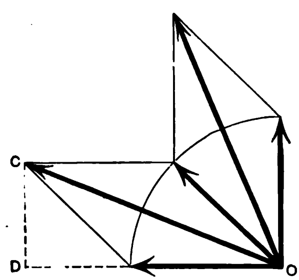


FIG. 2. VECTOR DIAGRAM OF A TWO PHASE THREE WIRE SYSTEM IN WHICH ALL THREE WIRES HAVE THE SAME CURRENT DENSITY.

three heavy lines, equal in length and 45° apart, represent the three drops. The resultant drop between the terminals of the middle and outside leg is equal to the line CO, and this is equal to the square root of the sum of the square of CD

and DO. It will be seen at once that DO is not equal to the double of one of the drops and CD is not equal to the single value. CD is equal to one of the drops multiplied by the sine of 45°, and OD is equal to one of the drops plus one of the drops multiplied by the cosine of 45°. Representing the drops themselves by D, we have resultant CO equals

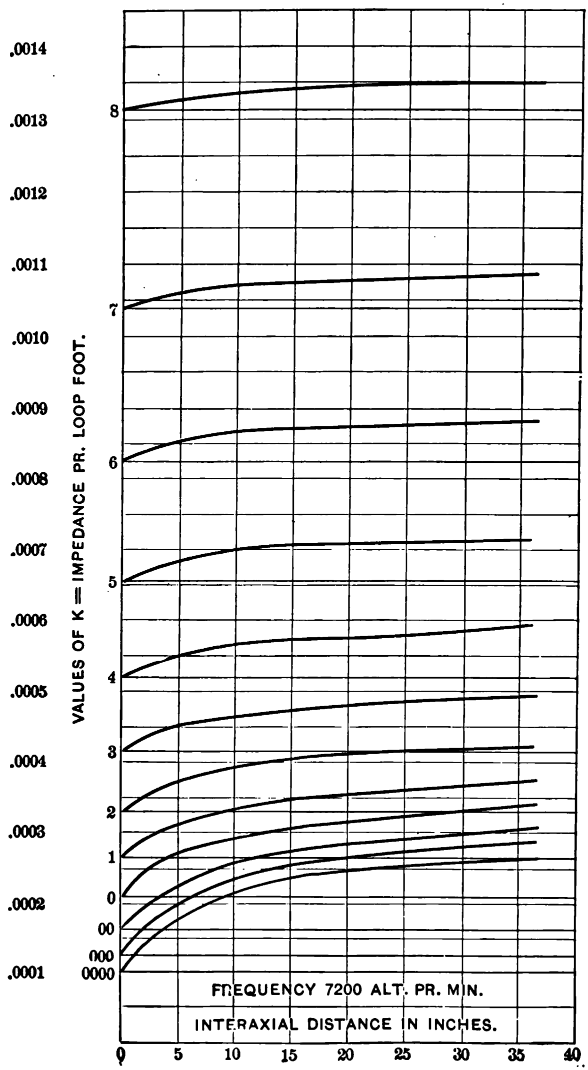
$$CO = \sqrt{\left(\frac{D}{\sqrt{2}}\right)^2 + \left(D + \frac{D}{\sqrt{2}}\right)^2}.$$

Performing the mathematical work indicated, we have resultant

$$CO = D \times 1.847;$$

whence it follows, if the resultant is to be 10 between the centre lines and the two outside lines, the drop in each individual line should be 5.414.

In some cases it is necessary to take account of the inductive drop in an alternating current line, and the amount of this drop depends upon the distance the wires are apart, the frequency, and the size of the wire itself. The formulæ and their application are a little complicated, and recourse may be conveniently had to the curves, Figs. 3 and 4. These curves represent on their horizontal axes the distance between the wires in inches. The vertical axes represent the impedance per foot, that is to say, the obstructive action that the line offers to the current flowing.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VALUES OF K = IMPEDANCE PR. LOOP FOOT.
8
7
6
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000
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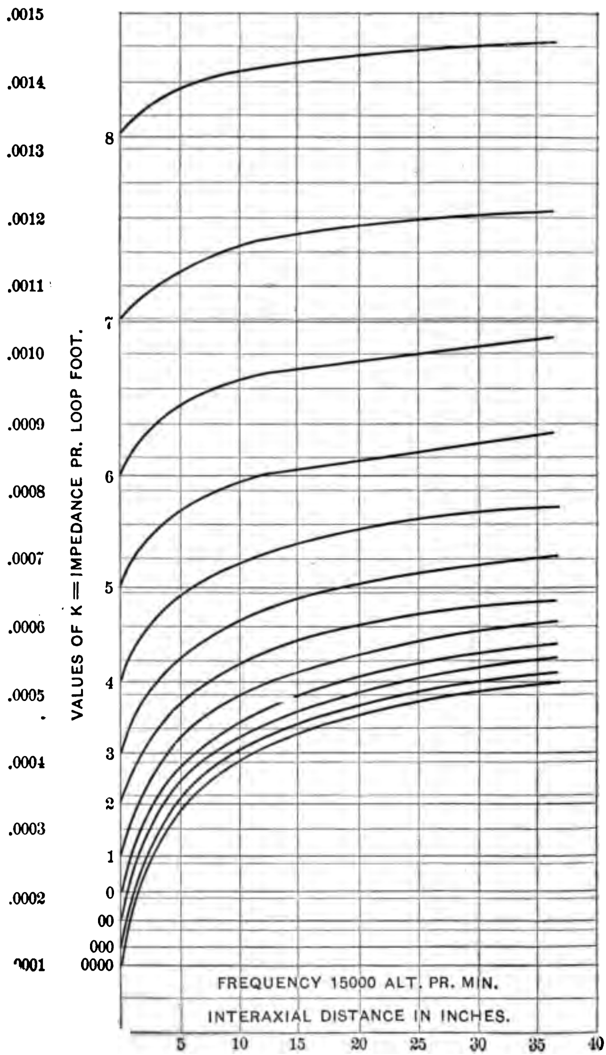
FREQUENCY 7200 ALT. PR. MIN.
INTERAXIAL DISTANCE IN INCHES.
0
5
10
15
20
25
30
35
40

FIG. 3.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VALUES OF K = IMPEDANCE PR. LOOP FOOT.
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FREQUENCY 15000 ALT. PR. MIN.
INTERAXIAL DISTANCE IN INCHES.
5
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15
20
25
30
35
40

FIG. 4.

Let it be supposed that we have calculated by the foregoing rules the ohmic impedance of the line, and, dividing by the length of the line, we have thereby calculated the ohmic impedance per foot. If we are to neglect inductive reaction of the line, we at once turn to the wire table and select a wire having that resistance per foot. If it is desired to take the inductance of the line into consideration, the ohms per foot as calculated by the foregoing formulæ should be doubled, thereby making the result the ohms per loop foot, and that figure should be selected on the vertical scale of the diagram, selecting a diagram of the proper frequency. On the horizontal line should be selected the interaxial distance in inches on the wires, and the point corresponding to this ordinate and abscissa will lie amongst the curves, and the curve nearest to that point is the size of wire required. If inductance is neglected, the straight line nearest that point is the size of wire required. An examination of the two diagrams will show a number of things with reference to line inductances. First, if the distance between wires is very small, line inductance is inconsiderable. If the axes of the wires are coincident, as in the case of the concentric cable, it practically disappears, that is to say, the curve and the corresponding straight line are coincident. Second, it shows that, if the size of the wire is small, there is little to choose between the curve and the straight line, the difference not being even one gauge of wire, Brown & Sharp. Lastly, if the frequency is

low, the inductance becomes inconsiderable, and, below 7,200 alternations per minute in wires not larger than 0000 Brown & Sharp, it can be neglected. The diagrams further show that, on a frequency of 7,200 alternations per minute up to No. 4 Brown & Sharp, it is unnecessary to make allowance for induction, as the true size of wire is less than one gauge away from the size of wire computed by the plain ohmic law, and, with 15,000 alternations per minute, any wire smaller than No. 8 has a negligible inductance factor. The foregoing curves and discussions take no account of inductance phenomena due to neighboring polyphase wires, and, in cases where this becomes important, the line is usually of such magnitude and involves an investment of money sufficiently large to justify extended special calculations, which are beyond the scope of this work.

CHAPTER IX.

ALTERNATING CURRENT MEASUREMENTS.

The student appreciates that the alternating current is not a steady current but rises to a maximum, dies away to zero, rises to a maximum in reverse direction, and repeats, and as the same is true of alternating voltages and alternating current power, it is evident that the alternating current ammeters and voltmeters and other instruments with their steady deflections, do not follow the current in all of its varying values, and its thousands of cycles per minute, but indicate some representative average value. This average value is known as the virtual or effective value, and volts and amperes measured by alternating current instruments are called virtual volts or virtual amperes. This value bears a peculiar relation to the many individual values which it represents, and is based on the equation

$$\text{Energy} = C^2R$$

which is well known in direct currents, and is also true of alternating currents flowing in simple circuits, the energy represented being that dissipated as heat in the circuit. In considering this equation for alternating current, R is measured in the same way as in direct current measurement, and as the energy is measured in watts, C must then be a value such that if squared and multiplied by R, it will give the energy dissipated in electrical watts. If the energy represented in the above equation is to be the average power, it is evident that C^2 is the average of

the squares of all the various values that the current obtains during a cycle of changes, and C alone or the current indicated by the alternating current ammeter, is therefore the square root of the average of the squares of the various individual values. By a similar voltage relation can be shown from

$$\text{Energy} = \frac{E^2}{R},$$

a well known direct current equation. If the energy is to be the average power, E^2 must be the average of all the squares that obtain during the cycle, and E must be the square root of the means of the squares. Hence the virtual voltage or virtual amperes indicated by the alternating current instrument is the square root of the mean square value.

An alternating current instrument must of course be able to give a deflection in one given direction no matter which way the current flows through the instrument. It is therefore usually built on one of two principles. The first of these principles is called the dynamometer principle. In this arrangement two coils are provided, one within the other. One coil is made movable on a pivot, and the current carried to it by suitable flexible connections. The other coil is stationary. For the voltmeter and ammeter these coils are connected in series with one another. A voltmeter arranged on this principle is shown in Fig. 1. If a direct current be sent through such an instrument, it is plain that the current carrying coils will repel one another and give a deflection in a certain direction. If the current is reversed through the coils, the deflection will be the same ount and direction because the current is re- both coils. If the current is rapidly and al-

ternately reversed, as is the case with alternating currents, there will still be a deflection, and it can be shown that this deflection will be equal to the square root of the mean square value of the current flowing through the instrument. In voltmeters the structure is so arranged that their circuits are practically non-inductive, and therefore the deflection is proportional to the voltage of the terminals of the instruments and can therefore be calibrated in volts. Fig. 2 shows an instrument of this type with its enclosing case. It is built so that the coils are peculiarly inclined with reference to each other, which has certain advantages of construction. If the instrument is to read in amperes, it is difficult to provide a moving coil which will carry the current because the connections leading into the same are so heavy that it is practically impossible to give them flexibility sufficient to render the instrument delicate unless mercury contacts are used. For this purpose recourse is had to the magnetic vane type of instrument in which the moving part consists of a piece of soft iron which sets itself in the field where the magnetic intensity is the greatest. This tendency is balanced off by either gravity or a spring. It is evident that such a magnetic vane would set itself in the field of greatest intensity whether the field were alternating or direct, and consequently such an instrument can be used for measuring alternating currents, and can be calibrated so as to indicate square root of mean square values. The dynamometer instrument will operate equally well on direct currents, but the magnetic vane instrument calibrated for alternating currents is not so satisfactory

on direct currents as a general rule. Such an instrument is shown in Fig. 3. Fig. 4 shows an instrument of the portable type adapted to measure amperes and constructed on the magnetic vane principle. In Fig. 5 is shown an instrument of the dynamometer principle which is adapted to measure currents. It is not a portable instrument for the reason that the moving coil has to be equipped with mercury contacts in order to enable it to receive its current and still be free to turn. In this instrument the coil is allowed to deflect only a limited amount, and is brought back to zero by twisting a balancing spring, the current being a function of the amount of twist that it is found necessary to give the spring to bring the coil back to its zero position. This is the true dynamometer principle, and instruments in which the moving coil is allowed to move and its deflection measured, are not as satisfactory under some circumstances.

In designing alternating current machinery, an effort is made to have the voltage generated thereby rise and fall in a certain series of smooth relations. These relations if plotted out with respect to time in the form of a curve, form what is known as the curve of sines. It can be shown that when an electro motive force is following the sine law, and rising from 100 positive to 100 volts negative alternating, the square root of the mean square value will be 70.7 volts. The circuit must be insulated so that it will bear a pressure of 100 volts because that is the maximum voltage that occurs on the line, and the one which is likely to break down the insulation. The maximum value of an alternating current volt-

age can therefore be obtained by dividing the virtual or effective value indicated by a voltmeter by .707.

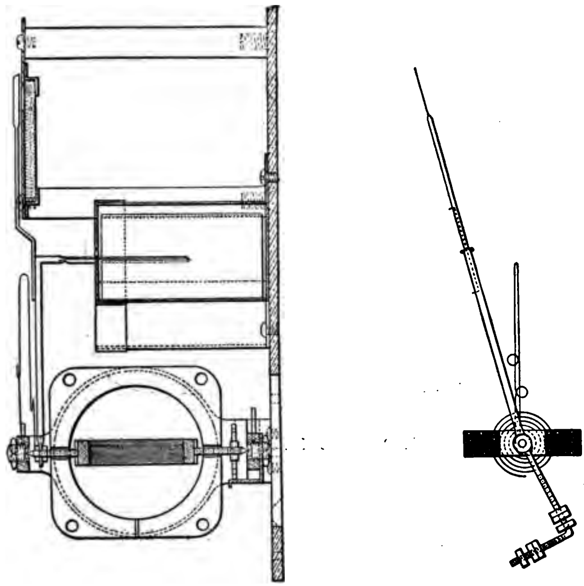


FIG. I. DYNAMOMETER VOLTMETER.

Alternating current power cannot as a rule be measured properly by simply taking the product of voltmeter and ammeter readings as is the case with direct currents. This product gives what is called the voltamperes and is a convenient figure in rating machinery, but it does not give true power and will not do so until multiplied by what is known as the

power factor, which is equal to the trigonometrical cosine of the angle of lag between the current and the voltage as plotted on a vector diagram. The power

FIG. 2. INCLINED COIL DYNAMOMETER VOLTMETER.

factor is very rarely unity, even in cases of loads supposed to be non-inductive. Therefore to measure power other means must be employed.

The most convenient of these is the use of the wattmeter, which will indicate power directly in true watts. The principle of the wattmeter is well illustrated in Fig. 5, when the moving coil is a potential coil of fine wire. It will be seen that the mechanism consists of two coils, one within the other. The stationary coil is connected in series with the line, and the movable coil is connected across the line, as shown in Fig. 6, which shows the connection

of a more portable type of instrument. The coils exert magnetic influence one upon the other and act to produce a deflecting force. The magnetic influence of the fine wire coil is directly in phase or step with the volts. The magnetic influence of the coarse wire coil is directly in phase with the amperes, and if these influences do not occur simultaneously, the instrument gives a lesser reading, the action of one upon the other thus taking account of the difference in phase relation, and making the resultant deflecting force proportional to the true mean power. The best form of wattmeter is that in which the coils are kept in the same relation to each other at all times, and the tendency of the moving coil to turn is balanced off by an adjustable spring, the torque necessary to do this being measured by an index on a scale. Fig. 5 illustrates this principle, the instrument shown is adapted to measure current, but its mechanical principle is the same. The needle in the top of the instrument is connected with the moving coil, and when power is applied it deflects smartly to the left. The balancing spring is provided with an index showing the exact distance it is twisted, and by turning a knob in the top of the instrument, a certain point will be found where the needle is restored to its original position of balance. The amount of twist in the spring is then read off, and properly calibrated, is equal to the true watts flowing through the instrument.

This form of instrument is not always convenient when the power is fluctuating, as it is difficult to follow such fluctuations with the torsion screw. Some instruments like that shown in Fig. 7 grad-

uate the indicator needle which then gives indications which can be added to or taken from the torsion head reading as the case may be. Where this does not suffice to follow the fluctuations, recourse must be had to an instrument which allows the moving

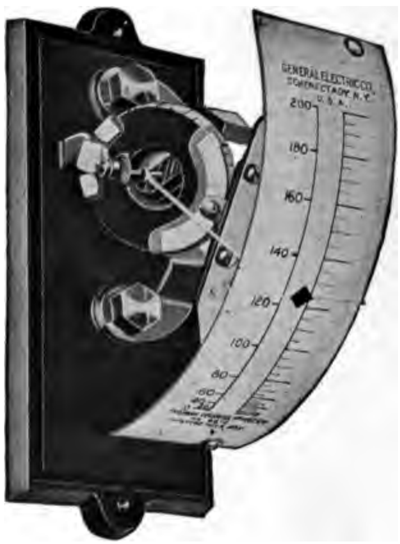


FIG. 3. MAGNETIC VANE AMPERE METER.

coil to deflect and measure with an index on a scale. This form of instrument is not quite as satisfactory on inductive load, but it is indispensable in many cases. Fig. 8 shows a deflecting wattmeter.

It is possible, however, to measure power without a wattmeter in numerous ways. It may be remembered profitably that any simple alternating current

circuit subjected to a known potential consumes the same amount of power whenever it is subjected to that potential and frequency. Thus if it were desirable to test different types of transformers under

FIG. 4. MAGNETIC VANE AMMETER.

identical loads, and only one wattmeter were available, so that the incoming watts could not be compared with the outgoing watts simultaneously with two instruments, the following plan could be adopted. Upon the load could be impressed a certain predetermined and measured voltage, and the watts measured directly with the wattmeter. Let us say that this indicated a load of 1,000 true watts. The transformer could then be connected in circuit and the wattmeter applied on the primary side, it being simply necessary to raise the secondary voltage to the same point that it was before. It would then be known that the secondary output was 1,000 watts

and the primary input could be measured by the wattmeter.

In simple circuits where there is no transfer of energy magnetically such as in the case with coil of wire containing no iron, the power consumed is always equal to C^2R. Thus, in such a case, where there is available an alternating current ammeter of known accuracy, and an ohmmeter, the resistance could be measured and the current and the power computed therefrom.

The power factor could also be readily found under such circumstances in the following way: the law of alternating circuits is as follows:

$$C = \frac{E}{I}$$

where I is the quantity known as the impedance of the circuit and is the combined retarding effect of resistance, inductance and capacity. It has also been mentioned that the true power is displayed by the following equation:

$$W = E\,C\,F$$

where F is equal to the power factor. Now since in simple circuits W is also equal to C^2R, we may place these two quantities equal to each other and thus obtain the equation

$$C^2R = E\,C\,F$$

whence $F = \dfrac{C\,R}{E}$

Thus with an ammeter and voltmeter, and an ohm-

meter, the power factor of a simple circuit can be obtained and a wattmeter will not be necessary, for all the quantities on the right hand side of the equation can be measured by the available instrument indications. It will be seen also that

$$F = \frac{R}{\frac{E}{C}}$$

Now E over C is equal to the impedance or apparent

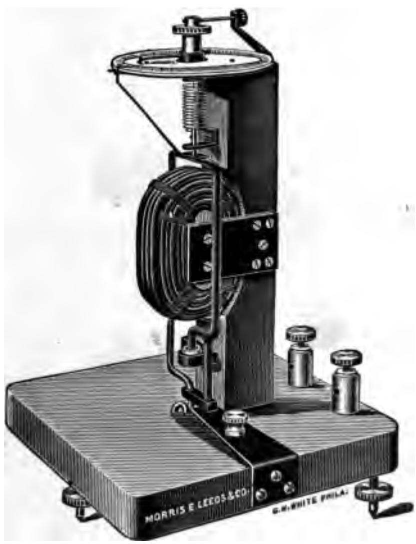


FIG. 5. PRINCIPLE OF ELECTRO-DYNAMOMETER FOR CURRENT MEASUREMENT.

resistance, and so we may say in simple circuits the power factor is always equal to the resistance di-

vided by the impedance. The impedance can be measured in ohms with an ammeter and voltmeter. To take a practical example, let us suppose that we have a coil operating 1,100 volts and containing no iron. It is therefore a simple alternating circuit in which there is no magnetic transfer of energy. Let us sup-

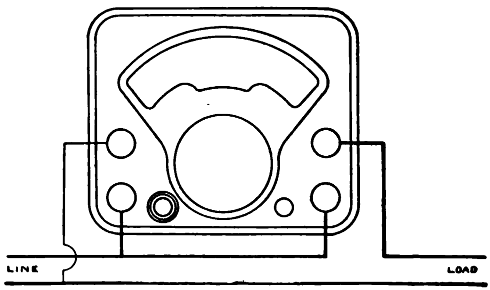


FIG. 6. WATT-METER CONNECTIONS.

pose that the resistance is equal to 10 ohms and that a measurement of the current gives a reading of 1 ampere.

The apparent energy or volt amperes is therefore

$$E = V C = 1100 \times 1 = 1100 \text{ watts.}$$

The true energy, however, is equal to

$$C^2 R = 1 \times 1 \times 10 = 10 \text{ watts}$$

and the power factor, that is the factor by which apparent power must be multiplied to give the er is equal to

$$F = \frac{10}{1100} = .009$$

and the current is therefore very nearly wattless.

Turning to a table of natural sines and cosines, we find that .009 is equal to the cosine of 89 de-

FIG. 7. WATT METER WITH GRADUATED INDEX.

grees 29 minutes, therefore the angle of lag is very nearly 90.

A convenient rough and ready wattmeter is a bank of 16 c. p. incandescent lamps. At full voltage each lamp takes very nearly 50 watts. This of course is an absorption watt meter, that is to say it not only measures the power but absorbs it also and can only be used in some cases. Thus if it is desired to

load a machine with 500 true watts, it would be necessary only to connect in circuit ten 16 c. p. incandescent lamps and bring them up to their true rated voltage. If the bank of lamps be calibrated by a wattmeter they are still more accurate, for then the actual power that they absorb is accurately known. If such a bank of lamps be employed, it is

FIG. 8. DEFLECTING WATTMETER.

better to operate them at 5 volts lower than their rating, measuring the power that they take at that voltage. The reason for this obtains in the fact that if they are run 5 volts under pressure, their life and permanence will be very much increased.

A convenient test which will be of great assistance miliarizing the student with alternating current

instruments is a transformer test. Let us suppose that we now have the problem of testing a 10 k. w. transformer operating at a nominal primary voltage of 1,000 volts and a secondary voltage of 100. Let it be required to find the efficiency of the transformer and to evaluate and tabulate its various losses. The secondary current is to be 100 amperes: the secondary volts 100. The primary volts will be about 1,000 and the primary amperes a little over 10. The ratio of turns or the ratio of reduction is ten. This enables us to select the best instruments for the work. If we are to make a thoroughly complete test, measuring everything with accuracy, we shall need for the primary measurements a voltmeter which will measure in excess of 1,000 volts. If this be a voltmeter equipped with a multiplier of 10, it can be used without the multiplier for measurements on the secondary side. Our primary amperemeter should have a range of about 15 amperes so that the 10 ampere reading will give a large scale deflection. If we had a large ammeter for the purpose of this reading, it is probable that our 10 ampere measurement would be a small scale deflection which would be practically unreadable, as alternating current instruments usually have very inferior graduations on their small readings. Our primary wattmeter should be selected with a maximum ampere capacity of about 15, and a voltage capacity exceeding 1,000. If this wattmeter also attains its higher voltage limit by means of a multiplier of 10, it will be found convenient, as we shall see farther on, in making secondary measurements.

The secondary instruments will be the following: An alternating current ammeter measuring 150 amperes; an alternating wattmeter with a maximum current capacity of about 150 amperes, and a voltage capacity of about 150 volts. We will probably be able to use the primary voltmeter without its multiplier for secondary voltage measurements. Lastly we should have a direct reading ohmmeter to enable us to measure the resistance of both primary and secondary coils, and a bank of incandescent lamps to give the transformer a load.

The first thing to do is to measure the resistance of the primary and secondary coils by the aid of the ohmmeter. Let us suppose that the results obtain as follows:

Primary resistance, 1 ohm.

Secondary resistance, .01 of an ohm.

From this we can at once compute the heat waste in the copper of the transformer coils by the simple C^2R formula. This will be as follows:

Primary watts lost in heating at full load, about

$$10^2 \times 1 = 100$$

for we know that the primary current will slightly exceed 10 for magnetizing purposes.

Secondary watts lost in heating at full load

$$100^2 \times .01 = 100$$

exactly, for the secondary current we will fix at 100.

The next thing to determine are the losses consumed in magnetizing the iron. For that purpose we will connect the secondary of the transformer to a source of supply at 101 volts, and will insert the

primary wattmeter without its multiplier. We use 101 volts because at full load, the secondary must generate this extra volt to provide for the C R drop in its coil. The current will be so small that the primary wattmeter will be able to carry it without difficulty. We must also have the voltmeter connected to the secondary circuit, because we must be sure that the secondary is excited at 101 volts, and must adjust our source of supply until this is a fact. The wattmeter may then be read, and we will suppose that its reading is 80. We should also have the primary ampere meter in series with the secondary circuit in this case to enable us to record the current used in this test. We select the primary amperemeter because in this case the current is small and will be very accurately read by this instrument. Let us suppose that the primary amperemeter so connected needs 3 amperes. We then have the following reading from our three instruments:

True watts....................	80
Volts	101
Amperes	3

From this we can compute the following results:
Apparent watts, 303.
Watts lost in heating the coil

$$3^2 \times .01 = .09.$$

We see from the foregoing that the circuit thus arranged has a power factor .264, the ratio of the true to the apparent watts, and we also see that all the losses are not consumed in C^2R, but that a very large percentage of them are consumed in some other way. This is plain because we have only .09 C^2R watts, and our wattmeter plainly shows that

the circuit is absorbing 80 true watts. The remaining 79.01 watts are therefore consumed in magnetizing the iron and would appear as heat in the iron core due to molecular friction of the iron particles during the various cycles of magnetism. The magnetizing current of 3 amperes would of course be only .3 ampere if the primary coil were doing the magnetizing, but it would be difficult to read so small a current, and hence it is much better determined by doing the magnetizing with the secondary and applying the transformer ratio.

From our previous discussions on transformers it will be remembered that in such a transformer as this the magnetism remains practically the same at full load and at no load, and is due to the difference of ampere turns between primary and secondary which is always a practically constant quantity. We may therefore write down the following losses of which we are absolutely sure when the secondary is delivering 100 amperes at 100 volts.

Secondary C^2R losses, 100.

Iron loss, 70.01.

We know then at full load the primary must supply the following:

Secondary output, 10,000 watts.

Secondary C^2R losses, 100 watts.

Iron losses, 79.01.

Primary C^2R, yet to be found.

The primary C^2R loss in this column has been left blank because it is plain that the primary coil must take more power than is represented by 100 amperes at 100 volts, in order to make up for the various losses in the apparatus. The most direct way

of measuring the primary C^2R losses is now to connect up the transformer to its lamp load on the secondary side, and to a source of electro motive force on the primary side, and to raise the value of this electro motive force until the secondary is delivering 10,000 watts at 100 volts. The primary watts could then be read off by a wattmeter connected in the primary circuit, and might be found to be 10280.68; the primary C^2R loss would then be 101.67, the difference between this and the other known amounts of power consumed. The primary current can of course be found readily by reading the instrument, and it will be found to read very closely to 10.08 amperes, the same value as would be obtained by solving the equation

$$C^2R = 101.67.$$

The primary volts, however, will be found to read about 1020. The distribution of energy in the system is therefore as follows:

Primary voltamperes, 10281.60.
Primary amperes, 10.08.
Primary volts, 1020.
Primary power factor, .99991.
Primary true watts, 10280.68.
Secondary volts, 100.
Secondary amperes, 100.
Secondary voltamperes, 10,000.
Secondary watts, 10,000.
C^2R losses in primary, 101.67 watts.
C^2R losses in secondary, 100 watts.
Iron losses, 79.01 watts.
Total losses, 280.68 watts.
Efficiency, 97.26 per cent.

It will be observed that the secondary circuit has no power factor as the true watts are exactly equal to apparent watts. The primary circuit has, however, a power factor because the .3 of an ampere which is required for magnetizing purposes is nearly wattless, and combines with the working current making a resultant with a slight lag. The primary power factor is very nearly unity.

The discussion of this test approximates in some cases and neglects in others some rather complex reactions which take place in the transformer and which the reader has not yet been prepared to consider, and only discusses the measurements with a view to showing how to use the instruments.

CHAPTER X.

THE INDUCTION MOTOR.

The direct current engineer is painfully familiar with the fact that a short circuited coil in a dynamo armature is the seat of very heavy currents when the machine is operating. He is also well aware that such a short-circuited coil causes a heavy back drag on the machine. That is to say the machine is harder to turn. It is plain therefore that if a direct current armature were short circuited completely by a continuous band of copper about the commutator, and revolved in an excited field, the back drag would be very powerful.

If the armature were held stationary and the field revolved, the same resistance to turning would be encountered for action and reaction are equal and opposite.

If in the foregoing combination the armature were released, it would revolve after the field and would lag behind it only enough to generate the currents necessary for its propulsion. It is clear that it could not revolve at the same speed as the field for the relation of the parts would then be exactly the same as if the machine were entirely at rest and even though the field were excited there would be no armature current generated and hence there would be no torque or turning effort. Therefore the armature will run at a little below the speed of the field. If the armature is given work to do this slip or speed difference will be still greater. It is plain that when

the slip is great the armature currents will also be large, and they will react heavily on the field magnet and destroy its magnetism. First, a heavily loaded dynamo field is weakened by just this reaction and requires a series coil to strengthen it. Second, the armature currents are alternating currents dependent in frequency upon the slip, and if they are large they become shifted in phase, thereby causing the conductors to be in a non-torque producing position at the moment they are carrying heavy current. When the slip increases a point may be reached where the armature currents are so large and so displaced in phase that they react on the field and reduce the torque. It is possible that, in spite of the enormous armature current, the torque may be reduced, due to reaction and phase shifting to less than when the armature current was weaker. If, therefore, we gradually increase the mechanical load on the armature arranged as has been described, it would at first carry the same, increasing its torque for the purpose and reducing its speed, until a critical point was reached, where further slip would result in reduced instead of increased torque. This would produce a still greater slip, and the process would be cumulative, that is to say, the armature would quickly come to rest and there remain, generating enormous currents of displaced phase and small torque-producing power, so that insufficient torque is produced to move the load.

The curve *a*, Figure 1, shows how the torque

varies with the slip in such a case. With zero slip the torque is zero also. As the slip increases the torque increases till a critical point is reached where the torque begins to decrease as the slip increases. When the speed of the armature is zero and the slip is a maximum, that is, equal to the speed of the field, the torque compares very unfavorably with the maximum torque of the machine.

If we should insert resistance in the armature circuit when things were in the condition just rehearsed, the armature currents would be reduced thereby and their reaction on the field due to magnitude and poor torque due to phase shifting, would be also reduced and the torque would increase and enable the machine to start a load that had stalled it heretofore. With the machine under way, the resistance would be a disadvantage, and therefore, after a certain point is reached, it will be best to cut the resistance out of the armature circuit, thereby sustaining the weakening current and torque.

If we should keep the revolving field frame of this peculiar machine stationary, and by some means cause the magnetism to shift from pole to pole in a series of regular gradations, it is plain that all of the foregoing effects would be produced This shifting action of the magnetism may be accomplished by means of polyphase alternating currents, and when this is done the machine becomes the induction motor, which has all of the electrical and mechanical characteristics which have just been rehearsed.

It is now necessary to investigate how this effect

of the revolving field is accomplished in order to complete our understanding of the general principle of the machine.

In order to investigate how this revolving field is generated, let us suppose we have an iron ring equipped on its inner surface with conductors as shown in Fig. 2. Let us divide these conductors into eight bands of five each, which is also indicated in the

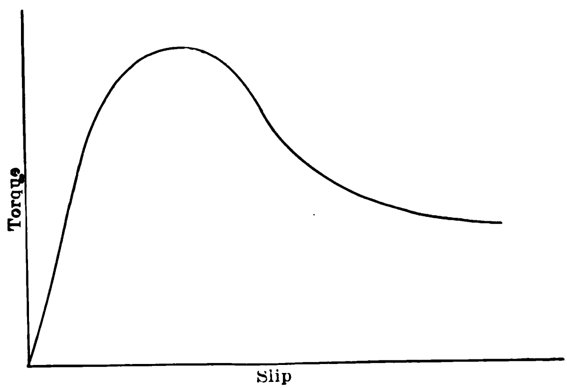


FIG. 1.

figure. Let these sets of bands indicated by A and B be supplied with current from the two phases of a two-phase dynamo. It follows at once that the current in bands A will be a maximum when the current in bands B is a minimum, and vice versa, and that while the shift from maximum to minimum is being made, intermediate conditions will prevail.

Let the crosses in the centres of the wires represent the retreating tip of an arrow flying in the direction of the current, while the dots depict the ap-

proaching point. In Fig. 2, therefore, the current in conductors B is zero, while in conductors A the current is at a maximum, for the conductors B being devoid of marks show zero current. Lines of

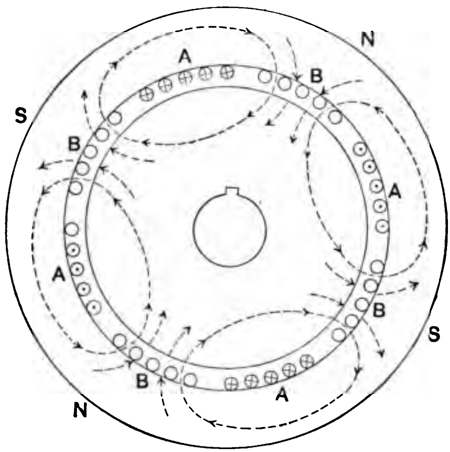


FIG. 2.

force will therefore circulate in the direction of the dotted arrows and we will have four distinct poles each surrounded by magnetizing current, passing away from the observer at wires A^1 and approaching the observer at wires A^2. At this condition, therefore, of maximum value of current in A, there will be established four poles marked N and S around the structure, and these poles will flux the iron armature depicted by the central circle. This condition however, only obtains for an instant, and as the

current begins to die away in coil A, it begins to rise in coils B.

Let us next consider the case where A is diminished and B is increased, until the currents in the coils surrounding the armature are of equal value, but are only one-half the maximum strength that they obtain throughout a cycle. Fig. 3 will

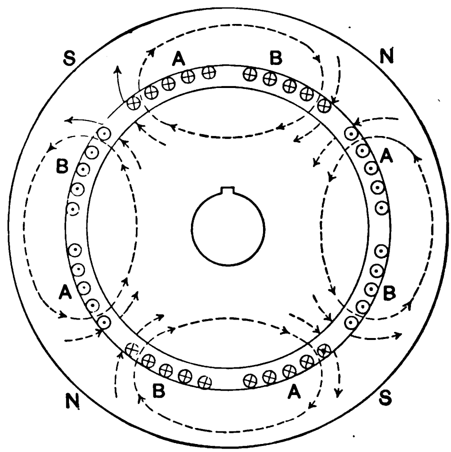


FIG. 3.

then depict the condition of affairs. Remembering that every conductor carrying a current away from an observer, must have a corresponding current carrying an equal amount of current towards the observer by the nature of the winding, it will be seen that the coils by this arrangement have split up into four bands of ten conductors each, half carrying

the current from the observer and the other half bringing it back again. The result will be that magnetic flux will flow as per dotted lines, and the points N and S will present to the armature four poles of practically the same strength as before, for while the currents surrounding them are only half

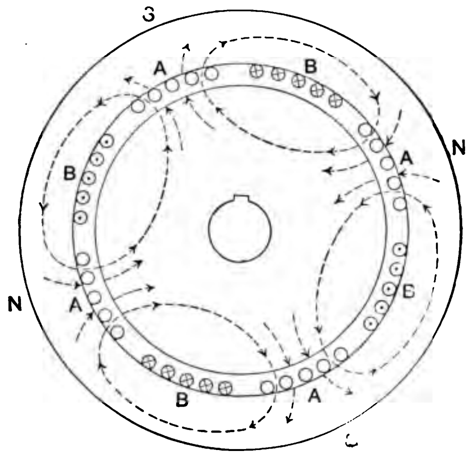


FIG. 4.

as strong as they were before, there are twice as many of them, and the ampere turns remain the same. It will be further noticed that these poles have shifted one-sixteenth of a revolution in a clockwise direction.

Considering now Fig. 4, the current in coils B is a maximum and that in coil A has died away to zero. Lines of force will flow as indicated by the dotted lines, and the poles still of the same strength

as they were before will be shifted another sixteenth of a revolution counting clockwise, and it is easy to see that as the cycles repeat themselves this operation will be repeated again, the poles still continuing to shift in sixteenths in a clockwise direction.

In investigating this phenomenon we have assumed convenient values of current, namely their maximum and half maximum values, but if we were to assume any value of the current from zero to maximum and compute by means of the known relation between the two phase currents the value of the current in the other phase and apply these values to the coils shown in the figue, we should find in every case that the magnetic poles developed would be surrounded by practically the same number of ampere turns, and be therefore of practically the same strength, and that the only effect of the varying currents would be to shift the polar position, which would be done by gradual progression instead of in jumps of sixteenths. Therefore this arrangement is equivalent to exciting the poles with direct current and revolving the whole machine.

Such a structure properly designed usually forms the stationary part of the modern induction motor, and is called the stator. The cylindrical armature equipped with wires parallel to its shaft and short circuited upon each other at their ends is dragged around after the revolving field, by reason of the principle outlined in the opening paragraphs of this chapter, and is called the rotor. It is plain that the rotor cannot revolve as fast as the field, for if it did

so it would keep up with the lines of force and no wires in the rotor would be cut by lines of force, hence there would be no currents generated in the same and therefore there would be no torque. As a matter of fact if we should drive the rotor mechanically up to synchronous speed as it is called, we should find that the only power necessary for this purpose is that sufficient to overcome the friction of the bearings.

The difference in speed between the revolving field and the actual number of revolutions of the rotor is called the slip. Thus if the field was revolving at 1,000 revolutions per minute and the rotor was only turning 900, the slip would be 100 revolutions. Sometimes this slip is expressed in percentage of the speed of the field. In the above case it would be

$$S = \frac{1{,}000 - 900}{1{,}000} = .1 \text{ or } 10 \text{ per cent.}$$

This is called by some writers the slippage. It is sufficient for the student of this article to realize that there is a difference in speed between the two quantities, that it can be evaluated, and that it is important.

It has been stated, and must be evident, that if there is no slip there will be no currents in the rotor and no torque, and that if there is slip, that slip will represent the speed at which the conductors in the rotor cut lines of force, and will therefore be proportional to the rotor currents and also to the torque if certain other considerations are for the present neglected; in fact the electrical effect on the rotor

will be just exactly the same as if the rotor revolved backwards at a speed equal to the slip, while the field stood still. Therefore the frequency of the rotor currents is also proportional to the slip.

In well designed induction motors the slip is very small, being only ten per cent. for small machines and rarely exceeding four per cent. in large machines. One can always gain an approximate idea of the load on an induction motor by measuring its speed and comparing it with the speed of the field, which can of course be computed by dividing the frequency of alteration by the number of poles

FIG. 5. SIMPLE ROTOR, SQUIRREL-CAGE TYPE.

or the number of cycles per minute by the number pairs of poles. In determining the number of poles on a motor, care must be taken to compute the number of poles *per phase* and not simply the number of bands of wires on the surface of the stator. Thus the machines shown in the foregoing figures are four pole machines. If by this simple experiment the

slip is found to be large, it may be assumed in a general way that the motor is working under a heavy load.

In practice the induction motor will be found to behave very much like an ordinary direct current

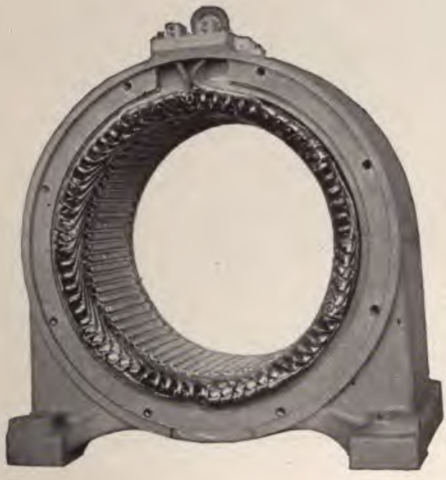


FIG. 6. TYPICAL STATOR WINDING.

shunt motor. It will have its highest speed at light load and it will slow down somewhat as the load comes on.

In electrical characteristics the induction motor behaves very much like an ordinary transformer. If the motor is driven by mechanical means at synchronous speed, no currents exist in its rotor cir-

cuits and the stator then becomes like the primary of a transformer with an open circuited secondary. It takes a small amount of current most of which is wattless for magnetizing purposes only, and the working component of this current is only sufficient

FIG. 7. COMPLETE MOTOR, SQUIRREL-CAGE ROTOR.

to overcome the heating losses in the stator wires and the iron losses in the stator and rotor. As load begins to be put on the induction motor, slip appears, and currents appear in the rotor winding, and as in the transformer additional current flows in the stator windings to make up for the demagnetizing action of the currents in the rotor windings so as to keep the magnetic field practically the same as it was before. As the slip and load become greater, the currents become heavier, and with them the

stator currents. If the currents in these two members now oppose each other with great magneto motive force, weakening the resultant field and reducing the torque, the alternative path through the armature also becomes less attractive to the lines of force and magnetic leakage appears,

FIG. 8. AUTO STARTER.

which is more prominent in the inductive motor than in the simple transformer, due to the relatively poorer magnetic circuit, due to the clearance gap necessary to permit the rotor to revolve. Leakage lines which do not cut both rotor and stator windings produce no torque, and their loss contributes to the lesser power of the motor. Hence, when

the slip is large, there will be reduced torque, unless some means are employed to keep down the excessive currents of displaced phase. The introduction of resistance into the rotor winding not only reduces the currents, but it improves their

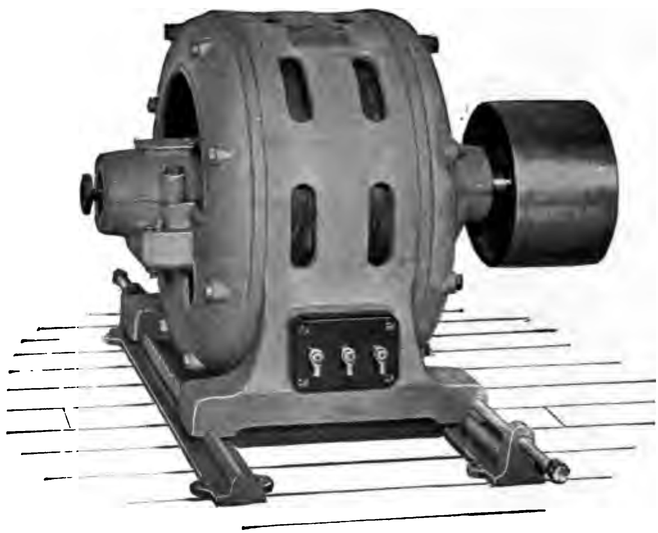


FIG. 9. INDUCTION MOTOR WITH RESISTANCE IN ROTOR CIRCUIT.

phase relation with reference to the stator winding as far as torque-producing is concerned.

The immediately preceding considerations are important because it is evident that at starting a motor the slip is equal to the speed of the field and is very large, in fact a maximum. Therefore in starting

induction motors it is customary to insert resistance either in the rotor or stator circuits, and to cut the same out after the machine has reached full speed. This enables the machine to start with a good torque and without taking excessive current. If the resistance however were permanently kept in circuit, it would have the effect of reducing the torque at full load. The machine would run with a greater slip than without the resistance and at a lower efficiency. Hence it is a very common thing to look for loose contacts in the rotor circuit when any undue amount of slip develops, and the motor is known not to be overloaded. The effect of putting resistance in the stator circuit is of course to operate the stator itself at a reduced voltage. This effect is more commonly obtained by means of an auto-transformer. A reduced voltage is applied by means of this device, and after the motor is well started, it is switched over on to the full line voltage.

An induction motor has a power factor less than unity, due to the shift of the phase of the primary current by reason of the wattless component required for magnetizing purposes. This power factor is considerably smaller than that which appears in transformers, and its smaller value is principally due to magnetic leakage, which makes the magnetizing current larger than would otherwise be the case. Hence induction motors are built with exceedingly small clearance gaps in order to minimize this trouble.

It has been stated that, when the slip becomes very large, the rotor currents react heavily on the stator due to their magnitude and displaced phase

FIG. 10. MOTOR WITH STATIONARY INDUCED WINDING.

and reduce the torque. Therefore, like the shunt motor, the torque of an induction motor is less at starting than at certain points of the load. If, therefore, the induction motor is loaded, the slip

and torque will increase and the motor will turn at reduced speed and carry its load. If, however, the load is carried to such a point that the reaction of the rotor becomes too great, the torque will not continue to increase but will reduce. The effect is cumulative, bringing the rotor quickly to rest, where it will stand, at the same time circulating enormous currents through its structure. Therefore fuses or overload limit devices are more important on an induction motor than a shunt motor, for if the latter is overloaded there will be plenty of distressing symptoms before the danger point appears, while the induction would simply quietly stop and then burn out.

In actual construction the induction motor stator carries a winding which strongly reminds one of the ordinary direct current armature winding. In fact if a direct current armature winding be tapped at equi-distant points and equipped with polyphase terminals, supplied from a polyphase generator, it would generate a rotary field, and some induction motors are built in this way. Other induction motors are built with independent circuits for each phase, in short the mesh or star winding or independent winding, as convenience and the exigencies of the case may dictate, are employed. The mechanical arrangement of the coils is the same as that used in designing direct current windings. The various slots in the stator and selected, each carrying currents in like directions, and are connected by end connectors to slots carrying current in the opposite

direction, the end connectors being arranged to lock into each other after the fashion of the Eickemeyer or straight-out winding. The rotor circuit and its windings is always of extreme simplicity. The simplest form is that shown in Fig. 5, in which the straight bars that form the rotor conductors are tied together at each end by a hoop of copper wire which effectively short circuits them to each other. The stator of this motor and the complete motor is shown in Figs. 6 and 7. In some cases it is found convenient to wind the rotor with a winding similar to that of the stator so that the ends may be brought out to rings for the purpose of inserting resistance in starting. A convenient means of inserting resistance in the rotor is to have a resistance concealed inside the rotor armature, to revolve with it, and arranged with suitable short circuiting terminals to engage with a sliding collar on the shaft which can be manipulated with a handle. Such a motor is illustrated in Fig. 9. Induction motors having squirrel cage rotors require an auto-transformer for use in connection with the stator for starting purposes unless the machine be very small, or unless it is started under very light load. Such an auto starter is shown in Fig. 8. It is plain that the motor could be built exchanging the function of the rotating members. That is to say, the revolving field could be on the revolving member and push the latter around by reacting on stationary short circuited conductors and some motors have been built in this way. There are, however, more advantages in the other forms

and few of these motors are now made. Such a motor is shown in Fig. 10.

Low frequency induction motors are readily built to have a very high power factor, but as the frequency increases, the difficulty of building the motor with a good power factor increases also, and with frequencies as high as 16,000 alternations per minute condensers are often employed to supply the lagging magnetizing currents.

CHAPTER XI.

The Rotary Converter.

It is often desired to change alternating current into direct current. For this purpose a rotary device of some kind is necessary. The student will readily appreciate the possibility of connecting a synchronous alternating current motor to a direct current dynamo and effecting the combination in this way, and the principles of this device are so simple that discussion of them in this chapter is not necessary.

It will be well understood that such a combined dynamo and motor could be driven by direct current and produce alternating current, or it could be driven by power and produce both direct and alternating current. It is, however, possible to secure all these results with a single machine weighing much less and costing much less. The only real difference between the two combinations as far as electrical performance is concerned is that the single machine does not possess independent current and voltage regulation, as does the combination device described in the opening paragraph.

If we take an ordinary Gramme ring armature revolving in a two pole field, as shown in Fig. 1, and tap opposite places in the winding with a lead and bring the same down to two collector rings on the shaft, we shall find that on revolving such an armature in an excited field an alternating current electro motive force appears at the two rings. It is

plain that this must be the case because we may consider the two halves of the ring as two equal coils connected in parallel, and as they revolve in the field, they fill with lines of force, first in one direction and then in another. The result cannot be anything but an alternating electro motive force, and if we connect a circuit across the collector rings we shall of course derive an alternating current electro motive force from this source. It is also plain that the operation of the machine as a direct current dynamo is in no way affected and we can draw direct

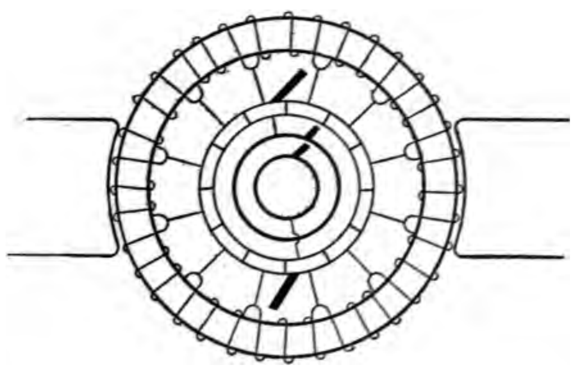


FIG. I.

current from the brushes and commutator in the ordinary way. It is further obvious that we could drive the machine as a direct current motor, and at the collector rings there would still appear the alternating current electro motive force, for we would still have identically equal electro motive force conditions as far as the coils and rings are concerned.

If we should draw alternating current from the collector rings at the same time that direct current was being fed to the commutator, there would appear in the armature conductors two currents superposed on each other. In reality there would be in these armature conductors only one current of varying strength, but that current would be the resultant of alternating current drawn from the rings on the one side and the direct current fed thereto on the other. The frequency of the alternating current would of course be fixed by the speed of the machine and the number of poles. In this case the number of cycles per minute would be exactly equal to the number of revolutions.

The value of the alternating current electro motive force will depend upon the speed of the machine and the strength of the field, but it is plain also that if the field be weakened, the speed of the machine would increase according to the laws of direct current motors. Therefore the alternating current electro motive force obtained from the rings would not be entirely dependent on the strength of the field, because whatever was lost by variation in field strength would be made up in part by variation in the speed of the device.

If the machine were driven so that the alternating current had a definite frequency, the conditions could be adjusted so that this frequency kept exact step with the frequency of another circuit, and the voltages being equalized, the machine could be connected to this circuit and could deliver power thereto. If the direct current source of supply were re-

moved from the armature, the machine would continue to run because it is operating at what is known as synchronous speed, that is to say synchronous with the alternating current to which it was connected, and currents would flow in the armature wires in such direction as to produce rotation under the influence of the magnetic field.

Considering any one conductor of the armature of the machine under these conditions, and assuming that at any given instant it was receiving current to cause it to be driven in the right direction, synchronous rotation will move that conductor through the field with just exactly the right speed so that when the current reverses due to the alternating current supply, it will be under the next pole and its reversed current will serve to drive in the same direction. Therefore by this arrangement we will have a direct current winding driven in an excited field and equipped with a commutator, a combination with which the student is already familiar, as a source of direct currents.

If the Gramme ring armature be equipped with three equi-distant taps and three rings, as shown in Fig. 2, three phase electro motive forces would appear at the three rings, in short, the foregoing reasoning would apply throughout. The same is true if four, six, eight or twelve rings and electro motive forces of appropriate phase be employed, and further consideration will show the above to be true of a drum as well as of a ring armature.

If this combination shown in Fig. 2 is taken in its simplest form, it will be found that the alternating

current electro motive force applied to the rings bears a fixed ratio to the direct current electro motive force taken from the commutator, and that strengthening or weakening the field has no influence whatever on raising or lowering the voltage. This is a condition which would not at first be expected to occur. There is no apparent reason why a direct current winding driven at a constant speed should not give a higher electro motive force at the commutator as the field strength is increased, and vice versa. The reason for this requires a little explanation:

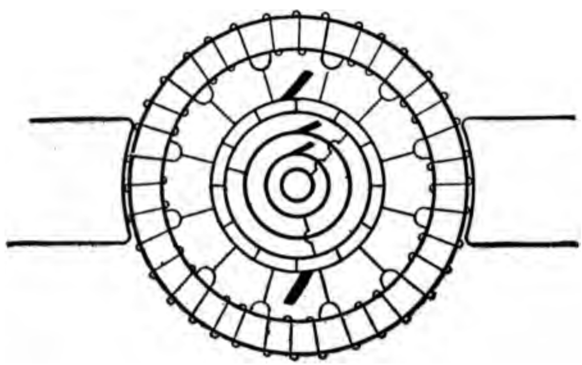


FIG. 2.

The electro motive forces ratio in a rotary converter are so absolutely fixed with relation to each other, that once started, a rotary converter will operate, receiving power at the alternating end and delivering it at the direct current end without any field whatever, and indeed some rotary converters have been built without any winding on their pole pieces.

Let us consider the armature alone. This has a distributed winding exactly similar to those employed in an induction motor and fed at equi-distant points thereon in an exactly similar way with polyphase currents. The result is a rotary field traversing the surface of the armature, and if the armature stood still, a properly designed short circuited rotor winding would revolve about it. In the rotary converter, however, this winding does not stand still but revolves at synchronous speed. As the winding revolves the field therefore stands still in space, and if this revolving armature with its stationary field be surrounded by a field excited with pole pieces as it is in practice, it is plain that the wires are cut not only by the flux from the excited field of the stationary part but by the flux of the stationary field which emanates from the armature itself under the conditions just described. Therefore an electro motive force generated in these wires is due to the resultant of these two fields. The field which is due to the armature stands still in space under constant conditions. If the conditions change, however, the field will either advance or recede to a new stationary position and make a corresponding change in the resultant flux. It is plain that if the field due to the armature registered with poles of like polarity in the excited field, the total excitation would be very much reduced, and conversely, if the field due to the armature were advanced so that it registered with poles of unlike polarity, the resultant flux would be very much increased.

In an alternating current dynamo a lagging current has a strong demagnetizing effect on the field, due to this very phenomenon. In an alternating current synchronous motor, in which class the rotary converter is, a lagging current very much strengthens the flux and a leading current weakens the flux. Conversely if the field flux is strengthened by increasing the exciting current in the stationary part, a leading current is produced, and if weakened a lagging current. Hence strengthening of the field of a rotary converter has the effect of shifting the field due to the armature to such a position as to render the resultant flux almost if not quite the same as it was before, and therefore a rotary converter transforming from alternating to direct current has practically a fixed ratio between alternating current and direct current ends irrespective of field strength.

The above being true, it may be asked why a field is required at all for a rotary converter. For the operation of the converter itself it is not necessary, and as has been stated before, a rotary converter will operate without any field windings. Under such circumstances, however, it takes a lagging current, which is objectionable, and increasing the field strength will not only do away with a lagging current, but if carried to a sufficient point will replace it with a leading current, and will therefore enable it to compensate for the lagging currents of other machines on the line, for instance, induction motors. This effect is most marked when the rotary converter is lightly loaded.

It is, however, possible to secure a voltage regula-

tion on the direct current end of the rotary converter, causing it to rise as the load comes on in precisely the same way that a direct current dynamo operates, and it will be readily appreciated that this feature is desirable. This is accomplished by increasing the strength of the field, but such increase of magnetism is only effective under certain peculiar line conditions and the corresponding rise of voltage is not due directly to the increase of the field strength itself. The operation of such an arrangement is as follows:

The line is equipped with reactance coils whereby the current is naturally lagging in its character. The increase of field strength produces a leading current in the rotary, thereby correcting the lagging current in the coils, and the inductive drop thereof. The alternating current potential at the rotary rings therefore becomes higher and with it the direct current potential at the commutator. Therefore when the line is equipped with proper inductance, a rotary may be compounded and will operate in all respects like a compound generator.

In respect to details of operation and management, the rotary converter differs from the direct current generator, and these details are reserved for a chapter to follow on the management of alternating current machinery.

Inasmuch as the voltage at the direct current terminals of a rotary converter is a function of that of the alternating end, it is interesting to examine the formula on which these ratios are established. Let E_d be the direct current voltage and E_a the alternating current voltage, and let N be the number of

collector rings on the converter, that is, the number of equi-distant points at which the armature winding is tapped. For a single phase converter there are two rings. For a two phase converter there are four rings. For a three phase converter three rings. For a six phase converter six rings. The deduction of the formula is rather too complicated for the scope of this work, but the formula itself is as follows:

$$Ea = \frac{1}{\sqrt{2}} Ed \sin \frac{\pi}{N}$$

Thus the effective electro motive forces of a single phase converter where the number of rings is two is

$$Ea = \frac{Ed}{\sqrt{2}} \times \sin \frac{\pi}{2} = .707\ Ed$$

because $\sin \frac{\pi}{2}$ is 1.

Therefore, if we were to supply a single phase rotary converter with 70.7 alternating volts, we should expect to receive at the direct current end 100 direct current volts, and in practice this value would be very nearly obtained, the only difference being the losses in the armature wave deformation, and influences of like character. For a three phase converter

$$N = 3$$

and the formula becomes

$$Ea = \frac{Ed}{\sqrt{2}} \times \sin \frac{\pi}{3} = .612\ Ed$$

for one third of π = 60 degrees, and the sine of 60 degrees is

$$\frac{\sqrt{3}}{2}$$

and the arithmetical solution gives the results given above. Therefore, if we wish to get 550 direct current volts from a three phase converter, it would be necessary to supply 550 × .612 or 337 alternating volts.

With a two phase converter N = 4.

$$Ea = \frac{Ed}{\sqrt{2}} \times \sin\frac{\pi}{4}$$

The sine of $\frac{\pi}{4}$ we know to be $\frac{1}{\sqrt{2}}$ and consequently

$$Ea = \frac{Ed}{2}$$

That is to say, the electro motive force between the adjacent rings of a two phase rotary converter is equal to one half the electro motive force at the direct current brushes.

CHAPTER XII.

Alternating Current Generators and Synchronous Motors.

Alternating current generators and synchronous motors are practically exactly alike, and as far as the methods of construction are concerned, the same remarks apply to either machine. The only difference between the two machines is their method of operation.

The simplest form of alternator is, of course, a single coil suitably wound upon a core and revolving in a magnetic field, the ends of this coil being brought out to two collector rings. As the coil empties and fills with lines of force, it gives an electro motive force first in one direction and then in the other, and as there is no effort made to commutate the same, this electro motive force appears at the terminals of the dynamo. An extension of this principle which provides a number of coils all in series with one another upon a revolving cylinder and an equal number of poles, comprises the principle of the method employed in building the first alternators. There is, of course, in such a case, but one alternating current, and therefore the machine is a single phase machine. A single phase winding built upon this plan is shown in Fig. 1.

The early alternators were like the early direct current machines, surface wound, the coils depicted in the figure being known as the "pancake" coil, and

machines of this type give an electro motive force which very closely approximated in its risings and fallings a sine curve.

With the advent of the toothed armature, alternators were built with toothed armatures also, and the resulting curve of electro motive force was very much peaked and distorted. The difference in the character of these currents was freely recognized and much discussion pro and con was had as to whether or no the peaked or the sine wave was the most suitable. At that time the alternating current motor had not come into prominence and was in its experimental stages and the peaked wave had many

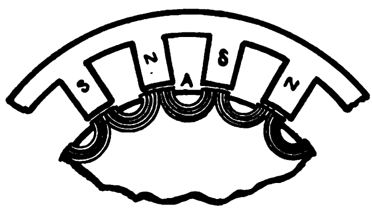


FIG. I.

arguments in its favor. However, as soon as alternating current began to be used for other purposes than for lighting, the form of the wave became more important, and it was soon seen that the sine wave was most desirable from every point of view. The toothed armature, however, with its great magnetic efficiency was not to be abandoned without an effort, and means were sought whereby this structure would give a sine wave as good if not better than its predecessors. This led to the general use of the distributed winding. The winding as depicted in

Fig. 1 being called a "concentrated" winding, that is to say, the coils were wound without overlapping, in large units and there were as many coils as poles.

In our discussion of the rotary converter we have seen that if we tap a direct current winding at two equi-distant points for every pair of poles and lead the ends out to collector rings, that an alternating current electro motive force will result. This arrangement provides a large number of coils per pole, and the waves of electro motive force from such an armature very closely approximates a curve of sines, even though the armature be toothed. In other words, the coil is spread out to cover the whole surface of the armature instead of concentrated in one large unit on one large tooth. Moreover the magnetic efficiency of such an armature is greater because of the shorter magnetic circuit, and the machine is better suited for operating in parallel with other machines. Consequently all modern alternators aim to have a distributed winding, that is to say, the armature has many slots and the winding covers the surface of the drum in much the same way as is the case with direct current machines.

As there are no commutation problems in the design of an alternator, it is not necessary to consider the inductance of a single bobbin with reference to anything excepting the production of a suitable form of electro motive force wave. It will be well understood that the fewer slots a machine has, and the fewer coils, the cheaper it is to build, and consequently most modern alternators have

enough coils to produce the sine wave, but in most cases not enough so that they could be connected to a commutator and give good direct current commutation except in the case of rotary converters where this is absolutely necessary.

Considering Fig. 1 again, it will be noted that between the coils there is a space A practically equal to the coil width, and it occurred to the designers that these spaces might be filled up also with coils, thereby producing a second winding from which an output equal to that of the first could be secured, and many early dynamos were built in this way. It

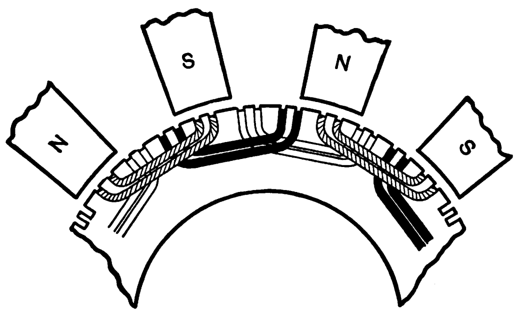


FIG. 2.

is safe to say that with this idea of increased output in view, a number of designers invented the polyphase dynamo long before they realized the value of its application. It was found that these two sets of coils could not be connected in parallel, and so each was led out to a separate pair of collector rings and the output utilized on separate circuits. Among the inventors who thus builded better than they

knew may be mentioned Gramme of France and James J. Wood of America.

It is easy for the reader of this article to see that, considering Fig. 1, coils placed in the middle spaces between those shown in the figure, would come under the poles a certain period after the other set of coils, and consequently the electro motive force in the two sets would not agree in phase but would be rigidly held a quarter period apart. These two

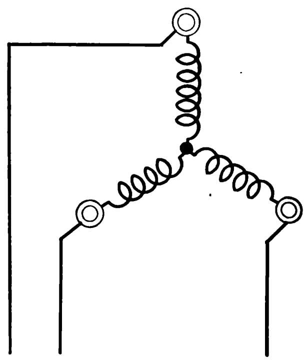


FIG. 3.

sets of coils, if connected in parallel would produce a short circuit. If connected in series they would produce 1.41 times the electromotive force of a single set of coils. It remained for Tesla by his invention of the polyphase motor to demonstrate that these currents in shifted phase could be utilized together in many cases with advantageous results, and in this way the polyphase dynamo, which had heretofore

existed simply as a means of getting greater output out of a single machine became a most important commercial dynamo. These things being known, it became at once apparent that the principle could be extended and several sets of coils could be placed on a single armature so arranged that each set would successively come under the influence of the poles, thereby producing currents in shifted phase with reference to their neighbors and each circuit could be led out to a pair of collector rings and utilized, and

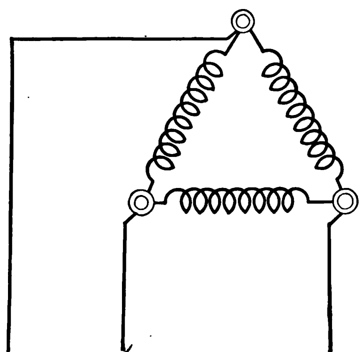


FIG. 4.

further developments and investigations showed that these sets of coils if properly designed, could be connected in star or mesh combination in precisely the same way, and on the same principle that transformers can be connected. Thus in Fig. 2 we have a dynamo with three sets of coils distributed to the extent that each coil is divided between two slots,

The arrangement shown is a common method of arranging the circuits of a three phase dynamo, and these sets of coils may be connected in gamma, as shown in Fig. 3, or in delta, as shown in Fig. 4.

A direct current winding tapped at equi-distant points and brought down to collector rings always produces a mesh winding.

Many modern alternators are wound on the Y plan. When an alternator is wound on the star sys-

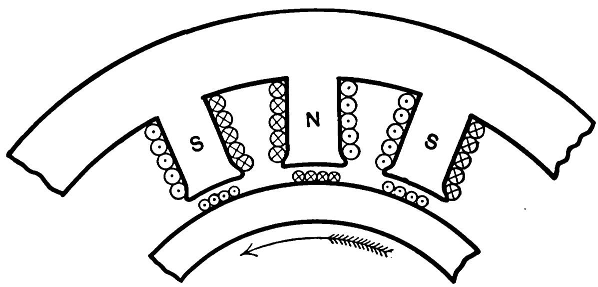


FIG. 5.

tem it is usual to bring out the centre of the winding to another collector ring. Thus a three phase dynamo may have four collector rings, the fourth ring constituting the centre of the star winding. It may have three rings, as shown in Figs. 3 and 4, or it may have six rings, in which the windings of each circuit are brought down independently, in which case the armature may be connected in star or mesh, as may be found desirable.

Similarly a two phase machine, while it usually has four rings, and two independent circuits on its

armature, may have five rings, the independent windings being connected together within the armature at their middle point, and that point being brought out to the fifth ring, or it may have only three rings, two of the ends of the winding being connected together and brought out to a single ring, the other two rings being reserved for the other two free ends. In that case the winding carrying two connections serves as a common return ring for the windings of the armature. This arrangement, however, is little used.

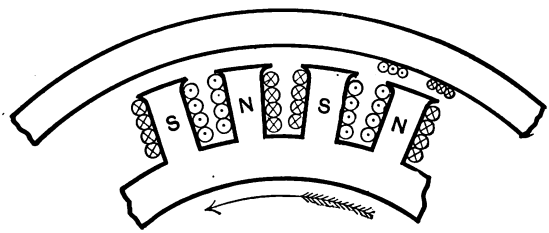


FIG. 6.

It is plain that an alternator being unhampered by a commutator may be conveniently built so that either member could be the revolving part, for instance, one method is that of having the wire in which the current is generated, that is to say, the armature, revolve as shown in Fig. 5, or the field may revolve, as shown in Fig. 6. The latter arrangement is very satisfactory and convenient, for there would then be necessary only two collector rings to feed direct current to the revolving field,

and the various terminals of the armature winding can then be brought out and connected together as may be found expedient. This is the method employed in all large alternators and in many of the smaller types; in fact there is little advantage in having the armature the revolving part unless it is

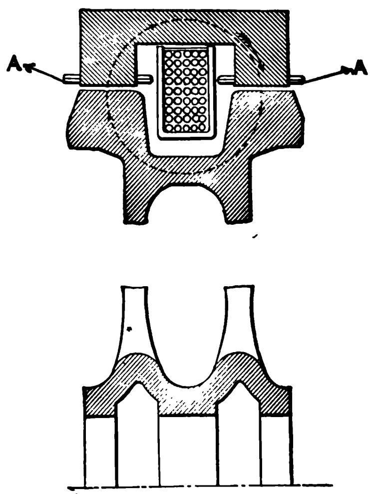


FIG. 7.

desired to commutate a portion of the alternating current for the purpose of producing a direct current for the field magnets for regulation purposes. It was found with early machines that unless some device of this character were employed, regulation would be very poor, but modern machines with toothed armatures and distributed windings can be built so that

the regulation is practically inherent, and in large units the changes of load are gradual and can be readily followed by hand. Hence in modern construction, machines with revolving fields are the rule, and the rotating armature is now the exceptional construction.

In order that an alternating current may be generated, it is only necessary that the generating coils be filled and emptied with lines of force at the proper intervals. This can be accomplished without the use of any moving wire whatever and machines of this type are called inductor alternators.

The simplest form of inductor alternator has for its principle the rotation of the core of the field magnet, the exciting wire being stationary. If we take a simple spool magnet with a cylindrical core mounted in bearings parallel to its length, it is plain that if there is clearance between the core and spool winding, that the former may be rotated while the latter is still, and if the core be equipped at its ends by projections radially disposed and these projections traverse in front of coils of wire, that the latter will fill and empty with lines of force, and we shall have an alternating generator without any moving wire. A diagram of such an alternator is shown in Fig. 7, and is the usual form of alternators of the inductor type. Of course it would be possible to place a coil in which current is to be generated, and an exciting coil side by side, and to suddenly move across the gap a piece of magnetic metal, which would complete the magnetic circuit of the two, and which would allow lines of force to flow from

one coil to the other, and by the equally sudden removal to de-energize the same. This principle has been employed, but not so generally and successfully as the one just cited. It is illustrated in Fig. 8, It is further evident that either of these structures could be wound with coils in such position as to successively come under the influence of magnetic flux in proper order and thereby give rise to several electro motive forces rigidly held a definite number of degrees apart in phase.

The synchronous motor is the exact counterpart of the alternator. Any alternator of the type discussed can be made to run as a synchronous motor. If such a machine be excited with direct currents and driven up to synchronous speed by some means and then connected to an alternating current line or

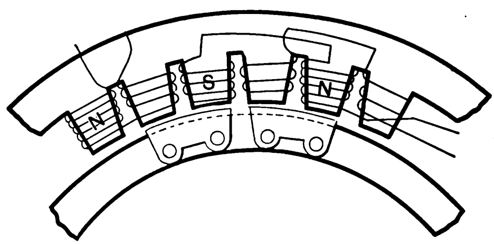


FIG. 8.

lines with which it is equal in phase and voltage, it will continue to run as a motor at synchronous speed, and load may be placed upon it up to a certain limit, beyond which it will be dragged out to synchronism and will immediately come to rest. Single phase synchronous motors have no torque whatever ex-

cepting at synchronism, and cannot start of themselves. Polyphase synchronous motors, if properly designed, have a slight torque at starting, which in some cases is sufficient to bring them up to synchronous speed provided that they are free of all load, and after synchronism is reached, the motor may be loaded. The synchronous motor is most suitable for large powers. In small units it is a very undesirable machine because of its inability to start under load, and the fact that it requires direct current excitation. Large power units, however, are frequently so arranged that starting under load is not necessary. The synchronous motor has an advantage that its power factor is under control by the simple device of varying the excitation. It is not only possible to make the power factor unity, but it is even possible to carry the work further and make the current a leading current, thereby compensating for the inductive drop in the line. In fact, this feature is so valuable that it is not uncommon to connect a synchronous motor to a system of circuits for no other purpose than improving the power factor. In such cases the synchronous motor is often called a condenser motor for the reason that its action is precisely similar to that of a condenser. The control of the power factor of a synchronous motor is much more complete when the motor is running without load.

CHAPTER XIII.

The Management of Alternating Current Machinery.

The most familiar alternating current generator is the single phase belted machine with concentrated windings, compounding coils and rectifier. These machines are used almost exclusively for lighting and are practically never run on inductive load or in parallel. Their operation is a very simple matter consisting merely first of bringing the machine up to speed, second, exciting it up to voltage, and third, switching on its working circuit.

The compounding coils of an alternator of this type are usually a very potent factor in maintaining the field as the load comes on, and in some cases they require to be helped out by means of the exciter rheostat. The greatest source of trouble in a machine of this type is the commutator. This is supposed to rectify a portion of the main line current for the purpose of exciting the series coils, the brush slipping from segment to segment as the alternating current passes through zero. If the phase of the alternating current shifts due to inductive load, proper point of commutation shifts also and if this is rapidly varying, it is a practical impossibility to follow it in its fluctuations. This is one of the principal reasons why the compounded alternator is not suitable for inductive loads.

The concentrated winding is also not suited to inductive loads for the reason that the reactions of the large concentrated coils are very heavy and reduce the voltage very materially, and this reduction of voltage by armature reaction is far more pronounced when the load is inductive for the following reason which holds true of any alternator. Considering Fig. 1, a diagram of an alternator, the wires are shown by circles and those carrying current contain either dots or crosses which also serve to indicate the direction of flow, if the dot be considered as the approaching point of the arrow and the cross its retreating tip.

When the load on an alternator is non-inductive, maximum current corresponds with maximum voltage. Maximum voltage occurs at the moment when the coil is beginning to fill with lines of force as in the position A B, and if maximum current corresponds, the field due to this coil will be principally expended in a cross magnetizing effect in that portion of the armature between adjacent pole pieces. If, however, the load is inductive, the maximum current does not occur in the wire till some instants after the maximum voltage has occurred, in other words the armature will have advanced further and maximum current will occur when the coil is in a position such as A_1 B_1. In this case it will be seen that the armature coil is linked with the magnetic circuit, and the direction of the current that it contains is opposite to that in the adjacent field winding. It, therefore, exercises a strong demagnetizing reaction. Moreover, in this position the coil is

carrying currents a proper direction to drive the armature instead of to be driven by it, consequently in this extreme position of phase displacement little energy is required to revolve the armature, in fact, only enough energy to overcome the frictional and various other losses of the dynamo including the C^2R loss necessary to force the power less current through the circuits. The above is useful in showing first, that the wattless current is very severe in its demagnetizing reactions, and second, that the wattless current can engage the current capacity of

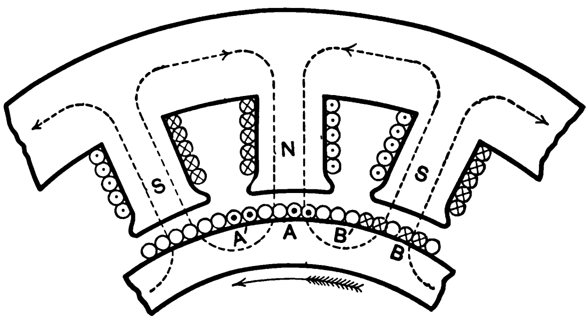


FIG. I.

the dynamo without requiring power in proportion to revolve it, in short, its exact nature is thus demonstrated.

To attempt to operate two alternators of the concentrated winding large tooth type in parallel is not very satisfactory though it can be done. The wave form given out by an armature of this type,

as has been stated in previous chapters, is an irregular peaked wave and the waves emanating from two different machines may not be at all alike. In order that two machines shall run in parallel together, their electro motive forces must be the same at every instant, and if their waves are different this is departed from, and currents will be exchanged between the machines. When one machine attempts to run faster than the other, waves of electro motive force of the two machines are displaced in phase instead of in exact opposition, and a resultant current between the machines at once flows which brings

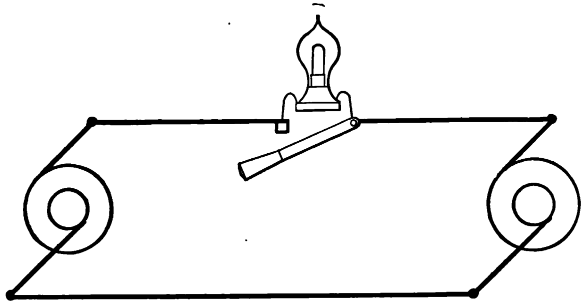


FIG. 2.

them back into step again. This is called the synchronizing current. If the waves are peaked, the slightest displacement in phase results in a very large difference of instantaneous electro motive force of the machines, and a very large synchronizing current flows which overdoes the work, accelerating the lagging machine too much and retarding the other machine too great a degree. This instantly displaces the phase in opposite direction and another synchron-

ous current is generated to restore the conditions, which also overdoes its work. This difficulty is apt to decrease rather than to diminish; and when machines do this they are said to be pumping or hunting, and the synchronizing currents frequently become so severe that it is necessary to separate the two machines.

When the wave is of the smooth sine variety such as obtains with a distributed winding, a slight displacement in phase only results in a small synchronizing current being generated, and the two arma-

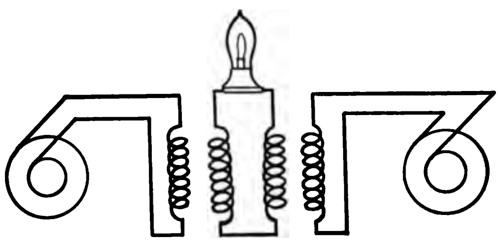


FIG. 3.

tures are brought back into phase without overtraveling. Hence machines with well distributed windings are invariably employed where good multiple operation is an important consideration.

A distributed wound single phase machine requires less skill in its operation than one of the old time single phasers. It sometimes carries a compound coil, though more often it has none, depending upon hand regulation. Its inherent regulation, that

is to say its maintenance of voltage under load without operating the rheostat is always good and but little hand regulation is required.

The polyphase generator operating singly requires no more attention than when operating on a single phase generator. It is necessary, however, that the phases be kept balanced, that is to say that the load on each phase be as nearly the same as possible, in short, the expedients employed in balancing up a three wire system can profitably be employed. In a large lighting station having street lighting circuits, it is very common to divide the latter up into groups, which can be thrown on any of the phases, and use them to balance off the commercial load over which the station has little control. If the phases are not kept evenly balanced, the voltage of the heavily loaded phase will be lower than that of the lightly loaded ones. If there are induction or synchronous motors on the line, these motors will tend to act as an equalizer absorbing power from the high voltage phase and delivering it to the low voltage phase. This, however, is very unsatisfactory from a standpoint of the owner of the motor, who naturally prefers to see his machine employed in doing his own work rather than occupying itself in transferring power from the light to the heavily loaded phases.

When it is attempted to run alternators in parallel, the skill of the central station manipulator is sometimes quite severely taxed. Before the machines can be switched together on the same busbars they must be in step and equal and opposite in voltage, for to

switch them together under any other conditions would mean a short circuit on account of the immense synchronizing currents which the machines will exchange between themselves. In order to determine whether two machines are in step, various devices are resorted to, the most common is that known as the synchronizing lamp. Two phases which are to be synchronized together are connected in series with a lamp interposed, the voltage of this lamp being equal to the sum of the voltages of the two machines. As the machines revolve going into and coming out of phase, this lamp flickers from a maximum to a minimum. When the lamp is dark the machines are in parallel. When it is bright they are in series with one another. When they are exchanging the parallel and series conditions very rapidly, the machines are of different frequencies, that is to say one is revolving faster than the other. The speeding machine should be retarded and the lagging machine should be accelerated. When this is properly done it will be noted that the flickering of the synchronizing lamp becomes less and less frequent, and that it changes more and more slowly from dark to bright. It is only when the lamp is dark, and the time which it has required to reach the dark condition from the last condition of brilliancy is some 5 or 10 seconds, (the larger the machine the longer the interval should be) before it is safe to throw them together. If they are not in exact step, connecting them together will cause the machines to exchange synchronizing currents and bring them into step; this in large machines means the sud-

den movement of many tons of metal which requires great power. Two machines could be instantaneously in absolute step, and equal in voltage for the instant, and yet one could be rapidly traveling ahead of the other. Switching them together under such conditions would necessitate the exchanging of sufficient synchronizing current to transfer the excess momentum of one machine to the other, and would be very likely to be an excessive current. Equal angular velocity on the armatures with reference to the pole pieces is very necessary, that is to say a given point on each armature must pass the same number of poles per minute. This is really of greater importance than that the machines should be exactly in phase, although the latter is important also.

The method of synchronizing with the lamp when the lamp becomes dark is called synchronizing dark. In high voltage machines of course a lamp cannot be employed without the intervention of two transformers as shown in Fig. 3. In such a case it becomes possible to connect the transformers so that when the machines are in phase the transformers shall be assisting each other in supplying voltage to the lamp, and maximum brilliancy of the lamp will then correspond to agreement in phase with the machines. This latter method is called synchronizing bright and is generally preferred because it is found to be easier to determine when a lamp is at full brilliancy than when it is absolutely currentless, for it may be carrying quite a substantial current without reddening the filament.

With very large alternators having enormous fly-wheel capacity the difficulties of synchronizing and the penalty for failure to synchronize when throwing machines in parallel are so severe that lamps as synchronizers are dangerous expedients, and other means must be adopted to determine whether the machines are in exact step and operating at the same angular velocity. Various devices have been employed. Telephones have been used, but the latter are so delicate that it is never possible to get the machines synchronized so perfectly as to produce exact silence, and they are therefore subject to the same criticism as lamps.

One of the most satisfactory arrangements is the Lincoln synchronoscope, due to Paul M. Lincoln, and now in almost universal use in large stations. It is illustrated in Fig. 4. This device indicates positively the difference in the frequency of the two alternators, and consists of a machine built exactly like an electric motor, except that the field magnet and armature are both laminated. The field magnet is excited with alternating current from one of the alternators to be synchronized. The armature of the synchronizer is wound with two coils at right angles to each other. Each of these coils is connected through

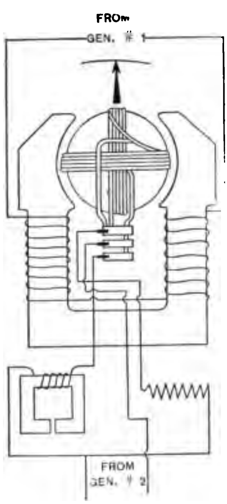


FIG. 4.

collecting rings to the terminals of the second alternator. One of the coils has in series therewith a non-inductive resistance and the other a large inductance. The shaft of this machine has attached to it a pointer which moves over a divided circle. The two coils at right angles to each other upon being excited from one of the alternators carry currents practically 90° apart in phase, and therefore generate a rotating field. If the alternator connected to the field frame of this machine be running very slowly, it will magnetize slowly, first in one direction and then in the other, and the rotating field will interlock with the stationary field and revolve the pointer. Conversely if the frequency of the generator connected to the field of the apparatus is the higher, the pointer will also be revolved but in the reverse direction. When the machines are equal in frequency but not in step, the pointer will be stationary, its position being dependent upon the difference in phase. Only when the machines are at exactly the same frequency and agree in phase will the pointer keep a vertical position, in which the coil connected to the non-inductive resistance will place itself so as to include the maximum number of lines of force in the magnetic circuit.

In using this device the switches are thrown which connect the synchronizer in circuit and it is observed to revolve in a certain direction, which shows that one of the machines is faster than the other. The lagging machine is accelerated and the other retarded until the pointer gradually

slows down to a very slow rotation. When the rotation is sufficiently slow and the pointer is at a vertical position it is safe to throw in the paralleling switches. The pointer, therefore, shows by its position the phase relation of the machines, and by its speed the difference in their angular velocities, and definitely fixes the two things that it is necessary to bring to equality before the synchronizing switches can be safely thrown. The device, of course, can be used directly or, as is more frequently the case, by means of transformers.

In engine driven alternators the turning moment is not uniform as is the case with water wheels or steam turbines. While the number of revolutions per minute may be quite constant, the angular velocity of the armature during the revolution will vary, increasing with the impulses of the piston and decreasing between the impulses. If two engine driven alternators are connected in parallel and the crank of the engines are not synchronized, one machine would be tending to surge ahead just at the time when the other machine lags behind. This is almost certain to result in severe pumping between the machines, and better operation will be obtained if they are separated and reconnected with their cranks as well as their phases in synchronism. This is not generally appreciated by those who have to operate such generators. The pumping is frequently noted and the units are separated to allow them to "settle down," when they are again connected together.

After two machines are connected together they will divide the load between themselves, but the ratio

of this division of load is not dependent upon the field magnetism as is the case with direct current generators. When the machines are multiple connected, one of them usually becomes the dictator of the speed of all the rest. This is usually the machine with the most sensitive governor if there be a difference between them. If any machine attempts to lag behind or lead ahead, synchronizing currents are exchanged so as to hold the machines together. Thus in a large number of generators driven by water wheels, the most sensitive governor will usually do all the governing, the speed of the other generators being controlled by synchronizing currents from the governor generator. The output of each generator will depend on the gate that the wheel is given. Similarly with steam engines connected to alternators, one of the sets is likely to do all the governing. To divide the loads between the machines better results will be found in adjusting the cutoff of the engines, giving longer cutoff to those engines which during the parallel running tend to allow the other machines to carry the load.

CHAPTER XIV.

THE MANAGEMENT OF ALTERNATING CURRENT MACHINERY. (CONTINUED.)

The alternator, both single and polyphase, has been often built with a rectifying commutator which supplies series excitation, and so many of these machines are now in use that it is well to devote a few paragraphs to them. As noted in the last chapter, they are not suitable for inductive load for the reason that shifting of the current phase must be accompanied by a shifting of the brushes of the rectifier in order that they may slip from segment to segment when the current has zero value. When operating such a machine, it is well to graduate the rocker arm of the brushes having an index for the various power factors and to consult a power factor indicator when making the adjustment. Unfortunately power factor indicators are not often found in plants with rectifier equipped alternators, for the instrument is as modern as the machine is antiquated. If, however, the case demands that inductive load be supplied from a rectifier equipped machine, the power factor indicator will be a very practical aid in setting the rocker. For every deflection of the instrument there is a non-sparking point on the rectifier which can be found and graduated for experimentally.

Rectifier alternators give opportunity for a variety of confusing connections which, however, have for their basis a few simple principles. The simple alter-

nator without any rectifier is usually connected as shown in Figure 1. The coils of the alternator armature are all in series and depend for excitation entirely upon an exciter dynamo. Two rheostats are usually provided. One is in the field of the exciter dynamo and controls its voltage and thus the current supplied to the alternator field. The range of this rheostat is limited by the commutation of the exciter. The other rheostat is connected in series with the exciter mains and controls the field current for the alternator directly. The range of this latter rheostat is unlimited as far as machine performance is concerned.

When the alternator is equipped with a rectifier, the most common way is to open the armature circuit before it passes to the rings and pass it through the rectifier as shown in Figure 2. The entire rectifier current is not usually allowed to pass through the series field of the alternator but a portion is deflected through a suitable shunt. The entire main line current, however, is rectified and appears in both the series field and shunt as undirectional pulsating current.

Rectified pulsating current is quite efficient in alternator excitation because it is at its highest strength at the same time that the armature current is also strong and hence stiffens the field at the moment when the armature reaction become heavy. In other words, it compounds the machine not only through the gradual rise or fall of the virtual ampere load it may be carrying but through its sinuosities of alternations also. The pulsating current, however, introduces a new loss into the machine namely, additional

hysterisis and eddy currents in the field magnets, due to the varying magnetic force which it impresses upon them.

When a rectifier equipped alternator suffers a short circuit, especially an inductive short circuit, they are usually formidable. The shifting of the phase of the current throws upon the rectifier the duty of breaking the main line current, not at its zero value, but at a value approaching the maximum. Indeed, if the lag is

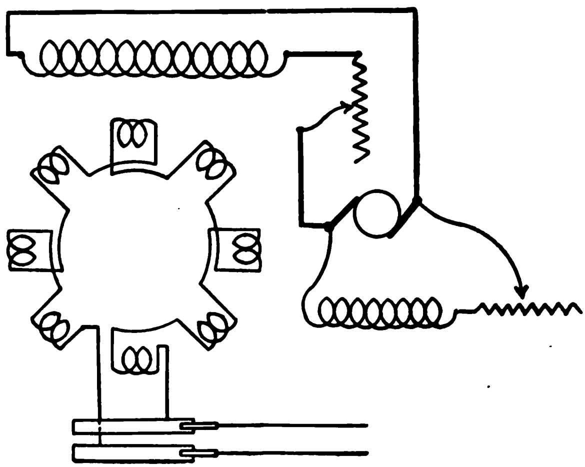


FIG. 1.

90 degrees, the maximum value of the current will obtain at the moment the brush passes from segment to segment. This the rectifier cannot do and a ring of fire surrounds it, causing the series coil to be practically short-circuited and reducing the excitation.

Hence it is very desirable that the rectifier should

not be required to work with the full main line current and to accomplish this several plans have been employed, with more or less success. One method is to place the shunt inside the alternator armature revolving with it. In this way the shunt can be applied to the incoming instead of the outgoing terminals of the rectifier, which will then only be required to commutate a portion of the main line current. This is

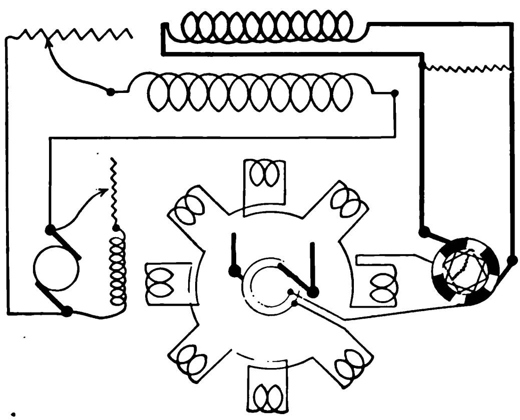


FIG. 2.

simple and effective, and in this case the shunt would carry alternating current while the series field would carry undirectional pulsating current. The connection of this shunt is indicated in Figure 2, by the little zig-zag line within the rectifier. Another way of accomplishing the same result and permitting more convenient disposal and construction of the shunt is to equip the alternator with a third ring connected to the winding before it passes to the rectifier. It is plain

that by connecting between the brush on the ring and the brush and ring on the other side of the rectifier that the latter will be shunted on its A. C. side and will therefore be relieved of the duty of commutating the entire current.

The use of the main line current for exciting pur-

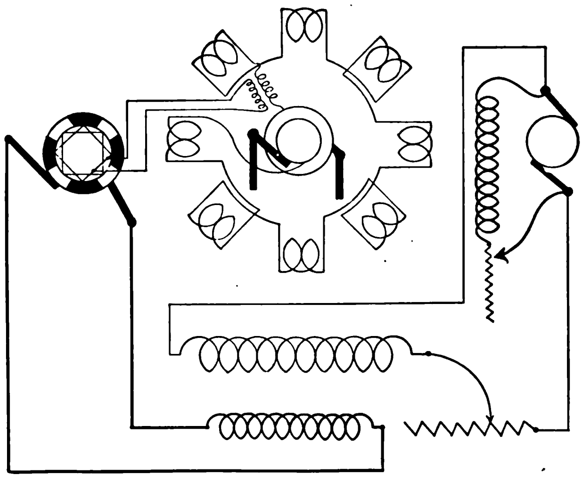


FIG. 3.

poses is, however, unsatisfactory even with shunting, for a certain number of ampere turns are required for the work, and if the amperes are made small the turns must be many and the voltage applied thereto correspondingly high. The whole device entails a machine loss proportional to the A. C. voltage at the rectifier terminals, the main line current and the power factor of the rectifier circuit. To keep the

A. C. voltage and with it the loss, at a minimum, the current in the rectifier must be large.

This necessity has been avoided in a very ingenious way in the type of alternator shown in Figure 3. Here the main line current is not carried to the rectifier, but a series transformer is inserted in the main line circuit, the secondary terminals of which are led to the rectifier for exciting purposes. This transformer can be shunted if desired for purposes of accurately setting the compounding. If the transformer were external to the machine, two additional rings would be required to lead the current into the rectifier, though if it were made of the auto type whereby primary and secondary were connected together at one terminal one ring would answer. In this case the other rectifier terminal could be had directly from one of the main line current rings. At least one company has built the transformer into the revolving armature, which does away with all extra rings, and to avoid extra weight they have utilized the spokes of the armature as the magnetic circuit of the transformer. This, of course, is not the best of magnetic circuits, but is not the less desirable, for it prevents the secondary voltage from rising to as high a value on open circuit as it otherwise would and improves the action of the rectifier.

In this way the necessary energy for series field excitation is raised in voltage and lowered in current value and the series fields of an alternator so equipped have more turns of smaller wire. The interposition of the transformer of limited dimensions makes it inadequate to transmit to the rectifier large amounts of destructive energy in case of short circuit.

CHAPTER XV.

Management of Induction Motors.

The induction motor in its electrical behavior resembles a transformer: in its mechanical behavior it resembles an ordinary shunt direct current motor.

If we were to open the rotor circuit of an induction motor, and to apply to the stator circuit the full voltage at which it is normally intended to operate, a very small current would flow, corresponding to the leakage current of a transformer, for in this condition the motor is nothing more or less than a transformer with an open circuited secondary. The minute current, which, by the way is not as small as in the case of an ordinary transformer, is called the magnetizing current. This is almost entirely a wattless current, very naturally so because it flows in a circuit of many coils surrounded by iron which it magnetizes. As there is an air gap between the rotor and the stator, the magnetic flux does not flow with the almost perfect coefficient of mutual induction that takes place in a transformer. There are leakage lines, that is to say lines which link with the stator windings but do not link with the rotor windings, and of these there is quite a perceptible percentage. The smaller the air gap between rotor and stator, the less this leakage effect will be, and the smaller will be the magnetizing current required to give the necessary flux of force. For that reason the clearance between rotor and stator, is in induction motors, made as

small as possible. This magnetizing current is in the stator circuit at all periods of operation. When the machine is fully loaded and the stator circuit carries working current as well, the working current combines with the magnetizing current forming a single resultant current which is the current taken by the machine. If the magnetizing current is large, its wattless character will, when combined with the working current, produce a resultant current which has quite a perceptible lag, or power factor, and because of this fact, it is very desirable to keep the magnetizing current as small as possible, as in that way the power factor of the machine will also be minimized.

If now we close the rotor circuit through a resistance, currents will flow in the same by induction in precisely the same way that they would flow if an ordinary transformer secondary was closed through a resistance, the primary being suitably excited. Additional current will at once flow in the primary to make up for the demagnetizing action of the secondary according to the transformer law, which has been studied in previous chapters. The secondary, however being free to move, will do so and cause the rotor to revolve according to the laws of the induction motor. As the rotor revolves, the secondary coils strive to reach such a position with reference to the primary coils that they will no longer react upon it, and to a large extent they succeed in doing this, and as a natural result the stator current diminishes. If the motor should attain synchronous speed, that is to say if the rotor should travel as fast as the re-

volving field, the stator current would drop off until it reached the original magnetizing value first spoken of in this discussion, in fact we may consider that an induction motor rotating at synchronous speed behaves exactly like a transformer with an open circuited secondary and a somewhat poor magnetic circuit, poor because of the air gap which it contains.

It will, of course, be appreciated that it is impossible, without extraneous sources of power, for the rotor to attain synchronous speed. There is a certain percentage of slip which has been discussed in previous chapters.

We will suppose that the induction motor is now equipped with a closed circuit rotor winding, and that voltage be suddenly applied to the stator coils. The result will be almost exactly the same as if we put the primary current on a transformer with a short circuited secondary. A very large stator current will flow and the rotor currents will also be very large. They will react heavily on the stator by reason of their magnitude and displaced phase, and almost destroy the magnetic effect generated by the magnetizing component of the stator current. The rotor will have only a very small torque. If it is free to turn, it will undoubtedly start and will rapidly come to a condition of full speed at light load, when the rotor currents will reduce to a very reasonable value, and the stator currents also.

Mechanically the machine will behave exactly like a shunt motor which has been abruptly connected to line, field and armature at once. In this familiar case the armature by reason of its low resistance, takes

so much current that it reacts heavily against the field and reduces the torque. The current taken from the line is abnormal, but presently the armature rising to speed, mitigates the conditions and the machine runs freely on light load. In short, with an induction motor we must treat it like a shunt motor. We must give it first its field, and then its armature. The ideal method is therefore to open the rotor circuit into a resistance, when the motor will get its magnetizing current and start with a good torque, and having once gotten up speed, the rotor circuit is closed, the process being somewhat analogous to the gradual cutting out of resistance in the armature circuit of a shunt motor. In some induction motors the rotor circuit is open and brought down to rings on the shafting, and from brushes on these rings wires are run to a suitable adjustable resistance, which being gradually cut out, starts the motor with good torque and without taking too much current from the line. As soon as the motor has reached working speed, the rings are short circuited on to one another. This is a very satisfactory arrangement but owing to the fact that an induction motor can be run without any brushes or rubbing contacts whatever, and owing to the fact also that rubbing contacts are a complication and have had an unfortunate history in electrical work, it is considered desirable to have a motor which has no rubbing contacts. Consequently induction motors have been built to accomplish this. One very satisfactory form contains the starting resistance within the rotor. As the latter revolves and attains speed, a sliding collar manipu-

lated by a lever short circuits this resistance, thus making the motor the analogue of a shunt motor having a starting box with only one notch. Even this, however, is a complication, and induction motors are built with very large squirrel cage windings which are permanently short circuited on each other, and motors such as this are often built in very large sizes.

Taking again the case of the direct current shunt motor, it could be started from line without abnormal current by simply placing a resistance in series with it and gradually cutting the latter out, and this could be done even if the field of the shunt motor were connected directly to the brushes. It would not have good torque on starting, but it could be brought up to speed without drawing too much current from the line. Similarly the induction motor with a closed circuit secondary, can be started from the line without drawing abnormal current, by the application of a lesser voltage than the working voltage, and after it has gained speed, full line voltage can be applied. Where the starting duty is not great, this is an arrangement that is much used, the reduced line voltage being arranged for by means of an auto-transformer. This is usually connected as in Fig. 1. On starting, a switch is thrown, as shown in Fig. 1, thereby applying the reduced voltage of the auto-transformer to the motor. When the motor has gained speed the switch is thrown to the right, thereby cutting out the auto-transformer and applying the line voltage directly to the motor. In factories where the

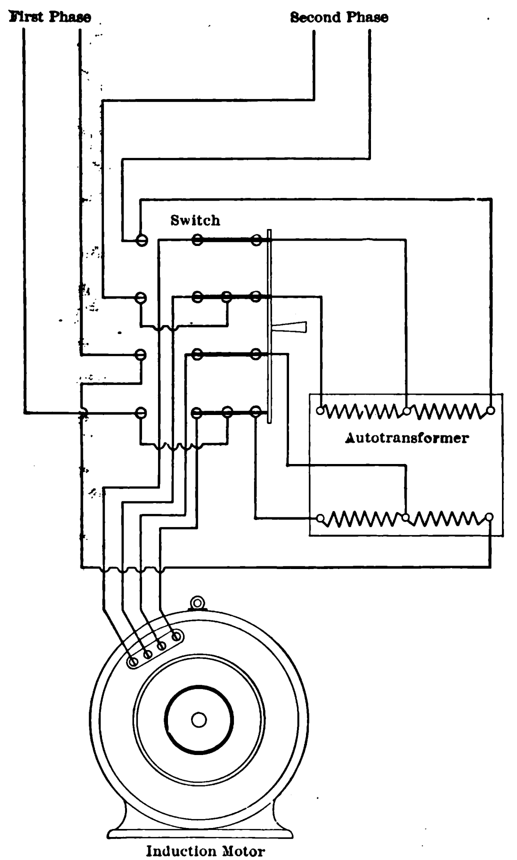

First Phase
Second Phase
Switch
Autotransformer
Induction Motor

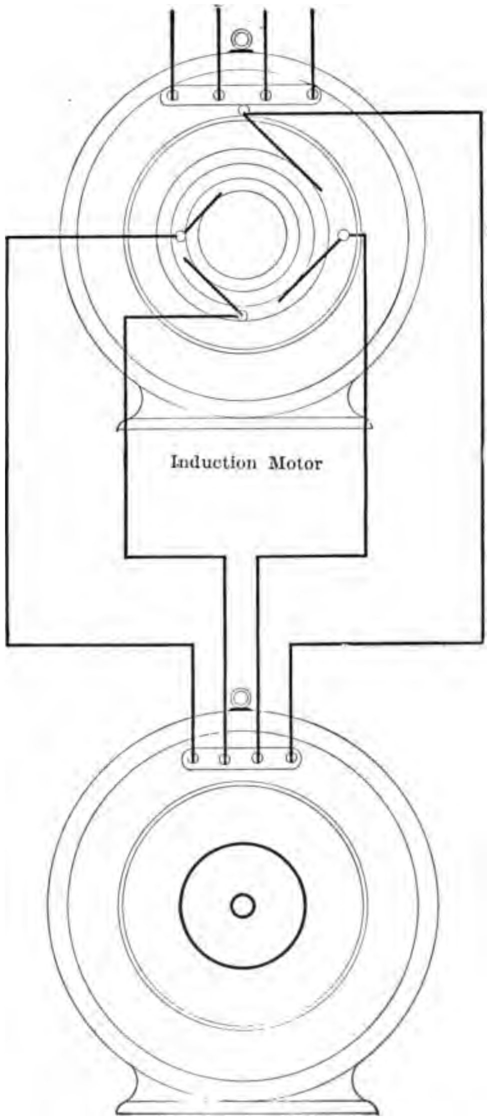
FIG. 1.

motor starts only with the line shafting, and the load comes on subsequently, this is a very satisfactory arrangement, and is much employed. For elevator work where the starting torque is very severe, the device of opening the secondary and employing an adjustable resistance is always used.

It will thus be seen that the induction motor resembling the shunt motor as it does, is not well suited for railway work, and for hoisting where the starting torque is very large.

Another method of starting an induction motor with a good torque is by lowering the frequency. With a reduced frequency a reduced speed does not represent as great a slip. Synchronous speed is not such a great percentage away, and the motor behaves proportionately better. It is of course not possible to reduce the frequency received from the line, but it is possible, with two induction motors to take advantage of this phenomenon.

We have seen that an induction motor when receiving currents in its stator generates alternating currents in the rotor. If the rotor be at synchronous speed, the alternating currents generated therein are zero. If there is a slight slip, the alternating currents generated in the rotor have a frequency which is proportional to the initial frequency and to the slip. Thus if a motor were being operated at 60 cycles and had a slip of 10 per cent., the frequency of the currents in the rotor would only be 6 cycles. If these rotor currents of reduced frequency were led away by slip rings to the stator of another induction motor, that motor would start with



Induction Motor

FIG. 2.

a good torque because its synchronous speed would only be one-tenth of its synchronous speed if excited direct from the line. This arrangement shown in Fig. 2 is called operating induction motors in cascade, and is a very good method of starting two induction motors. The first motor has a resistance, namely that of the secondary stator in series with its rotor, and therefore starts with a good torque. The second motor receives its currents at a reduced frequency, and therefore also starts with a good torque. This method is almost always employed in cases where induction motors are applied to railway work.

Induction motors for hoisting loads of heavy starting torque are objectionable, not only because of their inferior performance under such conditions but because of the heavy wattless currents that they draw from the line in the process of starting, reacting heavily upon the generators dipping the line voltage, and uselessly occupying the machines of the generating station. Until these objections are done away with, it is doubtful if the induction motors will find any wide application in such cases, any more than the shunt motor would be suitable for work of this kind.

If the induction motor be driven at a speed exceeding synchronism, and be connected to an alternating current line, it will become a generator and will deliver current to the line. It cannot do this unless it is connected to a line which is also supplied by machines of the synchronous type, because it cannot generate its own magnetizing current.

Let us suppose that we have a line which is supplied by an ordinary two phase alternator, and which supplies lights, induction motors and synchronous

motors. If we drive one of the induction motors by power at a speed above synchronism, it will contribute current to the line at proper frequency, and it does not require to be synchronized with the line, as is the case with an ordinary generator. The ordinary alternator could then be shut down, and the induction-generator would still continue to feed the line. If, however, the synchronous motors were shut down leaving nothing but induction motors and lamps on the line, the electrical energy would disappear from the system.

The reason for this is that the induction generator cannot generate its own magnetizing current, but must receive a reaction from the line which will permit the magnetizing current of displaced phase to flow in its fields. When operating as an induction generator, this magnetizing current must be a leading current. A synchronous motor provides such a current. If the induction generator be coupled into a line, its output is delivered to the line at a slight lag from the line current. The line is therefore able to supply the necessary leading component for magnetization.

The rotor circuit of an induction motor or generator simply needs to be a closed circuit winding. A solid cylinder of copper would revolve and give a torque, but it can be readily understood that the currents induced in such a cylinder would not flow on its surface in proper directions to give maximum results. To do this the currents must flow in bands parallel to the shaft, and consequently the machine should be wound so that the currents will be led in such directions. When it is desired to lead the

current off to rings, the winding must be symmetrica winding, quite similar to the stator winding so a to separate the currents of different phases to thei proper rings. When the machine is, however, alway operating with a short circuited rotor winding, plain series of parallel conductors joined together a the ends with rings in a squirrel cage fashion, wil answer all purposes. Induction motors are suitabl in almost every case, where a direct current shun motor would answer if the system were a direct cur rent system, that is to say in places where they ar to operate at full speed and with a reasonable loa and are only started occasionally. Where there i much starting and stopping they are not suitable.

In the case of large machines it is almost alway better to use a synchronous motor, provided th machine can have attention, that is to say it is bette for the power house. The user can get as good satis faction, in fact better satisfaction out of an inductio motor because it is less trouble, but the synchronou motor having a power factor which can be mad unity, or even arranged to compensate for th power factors or other devices on the line, is ver desirable from a station man's standpoint, because relieves his machines of much idle current which oc cupies their capacity and is detrimental to their regu lation.

The induction motor sometimes affords a ver pretty illustration of this idle, or wattless, curren phenomenon, especially when used in elevator wor with an over-counterweighted car. With the ca over-counterweighted, it will rise of itself and driv

the induction motor after it is once started. If a voltmeter, ammeter, or wattmeter be connected with such a motor, it will be found that after the car has once started, both voltmeter and ammeter will indicate, while a wattmeter shows zero reading. The current shown by the ammeter is the magnetizing current and is practically wattless. This magnetizing current flows in the line and in the generator at the power house. It does no useful work, it reacts on the power house machines, making it more difficult for them to maintain their voltage, and occupies much of their capacity. Therefore it can be readily seen that it is a decided inconvenience to the central station man, and for that reason is to be avoided.

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